Space Tethers 101

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www.tethers.com
Agenda

- About Tethers Unlimited, Inc.
- What’s a Space Tether?
- History & Status of Tethers
- Space Tether Physics
- Electrodynamic Propulsion
- Momentum Exchange Propulsion
About Tethers Unlimited, Inc.

- Founded in 1994 by Robert L. Forward & Robert Hoyt
- NASA SBIR & NIAC funding fueled initial growth
  - 2005 NASA SBIR “Success Story” Selection
- Successfully completed >70 contracts for NASA, DARPA, Navy, AFRL, Army, & industry primes
- Designed, built, launched, & operated a 3-picosecond satellite space flight mission in 2007, for less than $1M
- 7 Patents on space technologies
- Core Technologies:
  - Tether Propulsion & De-Orbit Technologies
  - Software Defined Radio Comm. and Nav. Sensors
  - Deployable Apertures and Structures
  - Additive Manufacturing of Spacecraft Components
  - Space Robotics
  - Optical Fiber Tether Dispensers for Mobile Robots
Space Tethers

- Long, thin cable or wire deployed from a spacecraft
- High strength tethers can enable momentum transfer from one spacecraft to another
- Conducting tethers can create propulsive forces through Lorentz force interactions with the Earth’s magnetic field
High-Strength Space-Survivable Tether

- Materials available today (e.g., Spectra, Dyneema, Zylon) are sufficient for most applications.
- Hoytether design provides structural redundancy to enable high survival probability for multi-year durations.
- Can incorporate conducting elements to enable electrodynamic operations.
Space Tethers: Cross-Cutting, Game-Changing Benefits

- Electrodynamc Tether: Orbit-Raising and Repositioning
- Drag-Makeup Stationkeeping for LEO Assets
- Rendezvous with and remove many objects with small system
- Capture & Deorbit of Space Debris
- Momentum-Exchange Launch-Assist & Orbit Transfer
- Formation Flying for Multi-Point Science & Long-Baseline Sensing
- Fully-Reusable In-Space Upper Stage
- Continuous Maneuvering & Plane Changes

Propellantless propulsion enables large $\Delta V$ missions with low mass impact

- Perpetual stationkeeping without resupply costs
- Precise & variable long baselines without propellant
History & Status of Space Tethers
### Space Tethers: Prior Missions

<table>
<thead>
<tr>
<th>Year</th>
<th>Mission</th>
<th>Type</th>
<th>Description</th>
<th>Lessons Learned</th>
</tr>
</thead>
</table>
| 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  
+ 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 contacts 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  
+ Demonstrated controlled retrieval of tether |
| 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
# Early Rocket Test History

<table>
<thead>
<tr>
<th>Rocket #</th>
<th>Date</th>
<th>Successes/Failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>18 Mar 1942</td>
<td>• Gyro &amp; propellant feed failures</td>
</tr>
<tr>
<td>3</td>
<td>16 Aug 1942</td>
<td>• Nose broke off</td>
</tr>
<tr>
<td>4</td>
<td>3 Oct 1942</td>
<td>• Success</td>
</tr>
<tr>
<td>5</td>
<td>21 Oct 1942</td>
<td>• Steam generator failure</td>
</tr>
<tr>
<td>6</td>
<td>9 Nov 1942</td>
<td>• Success</td>
</tr>
<tr>
<td>7</td>
<td>28 Nov 1942</td>
<td>• Tumbled</td>
</tr>
<tr>
<td>9</td>
<td>9 Dec 1942</td>
<td>• Hydrogen peroxide explosion</td>
</tr>
<tr>
<td>10</td>
<td>7 Jan 1943</td>
<td>• Explosion on ignition</td>
</tr>
<tr>
<td>11</td>
<td>25 Jan 1943</td>
<td>• Trajectory failure</td>
</tr>
<tr>
<td>12</td>
<td>17 Feb 1943</td>
<td>• Trajectory failure</td>
</tr>
<tr>
<td>13</td>
<td>19 Feb 1943</td>
<td>• Fire in tail</td>
</tr>
<tr>
<td>16</td>
<td>3 Mar 1943</td>
<td>• Exploded in flight</td>
</tr>
<tr>
<td>18</td>
<td>18 Mar 1943</td>
<td>• Trajectory failure</td>
</tr>
<tr>
<td>19</td>
<td>25 Mar 1943</td>
<td>• Tumbled, exploded</td>
</tr>
<tr>
<td>20</td>
<td>14 Apr 1943</td>
<td>• Crashed</td>
</tr>
<tr>
<td>21</td>
<td>22 Apr 1943</td>
<td>• Crashed</td>
</tr>
<tr>
<td>22</td>
<td>14 May 1943</td>
<td>• Cut off switch failed</td>
</tr>
<tr>
<td>25</td>
<td>26 May 1943</td>
<td>• Premature engine cutoff</td>
</tr>
<tr>
<td>26</td>
<td>26 May 1943</td>
<td>• Success</td>
</tr>
<tr>
<td>24</td>
<td>27 May 1943</td>
<td>• Success</td>
</tr>
<tr>
<td>23</td>
<td>1 Jun 1943</td>
<td>• Premature engine cutoff</td>
</tr>
<tr>
<td>29</td>
<td>11 Jun 1943</td>
<td>• Success</td>
</tr>
<tr>
<td>31</td>
<td>16 Jun 1943</td>
<td>• Premature engine cutoff</td>
</tr>
<tr>
<td>28</td>
<td>22 June 1943</td>
<td>• Exploded in flight</td>
</tr>
</tbody>
</table>

80% Failure Rate of Early Missions
Past Space Tether Experiments

- Rotating tethered capsule experiments during Gemini missions
- Small Expendable Deployer System (SEDS)
  - SEDS 1: de-orbited a small payload using 20 km tether
  - SEDS 2: demonstrated controlled deployment of a 20 km tether
  - PMG: demonstrated basics of electrodynamic physics using 500 m conducting wire
- Shuttle Tethered Satellite System (TSS) - 20 km insulated conducting tether
  - TSS-1: 200 m deployed, demonstrated stable dynamics & retrieval
    - Last-minute S&MA demanded design change resulting in oversized bolt that jammed deployer (configuration control process failure)
  - TSS-1R: 19.9 km deployed, >5 hours of excellent data validating models of ED tether-ionosphere current flow
    - Arc caused the tether to fail (contamination of insulation & failure to properly test tether prior to flight)
- TiPS - Survivability & Dynamics investigation
  - 4 km nonconducting tether, ~1000 km alt, survived over 10 years on orbit
- MAST – low cost tethered CubeSat experiment
  - Release mechanism malfunction prevented full deployment of tether
- YES-2
  - Computer resets during deployment prevented proper control of deployment
- T-Rex (JAXA)
  - Demonstrated conducting tape deployment current collection on sounding rocket

Past missions demonstrated stable tether deployment and physics of electrodynamic propulsion

Mission failures were due to design, QA, & process errors, not due to fundamental physics

Significant, predictable orbital maneuvering with a tether still needs to be demonstrated
Space Tether Physics
Gravity Gradient

No Tether

Tether forces satellites to co-orbit at center of gravity’s orbital velocity

Gravity gradient provides restoring force to align tether along local vertical
Electrodynamic Tether

Deboost/Power Generation

1. Gravity Gradient Tensions Tether
2. Motion-Induced $\mathbf{V} \times \mathbf{B}$ Electric Field
3. Tether converts orbital energy to electrical power in series load
4. \( \mathbf{J} \times \mathbf{B} \) Lorentz Electrodynamic Force Deboosts System

Boost Mode

1. Gravity Gradient Tensions Tether
2. Tether Control Module Drives Current Along Tether
3. \( \mathbf{J} \times \mathbf{B} \) Lorentz Electrodynamic Force Propels System

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Electrodynamic Propulsion Fundamentals

• Conducting wire deployed from an orbiting spacecraft

• Motion of wire through Earth’s magnetic field induces voltage along the wire

\[ V = L \cdot (v \times B) \]

• Currents flowing in the wire generate forces on the wire through Lorentz interactions with the Earth’s magnetic field

\[ F = J \times B \]

• Same fundamental physics as electric motors & electric generators

• Conducting plasma in ionosphere provides a mechanism for ‘closing the current loop’

• The Earth serves as the reaction mass for conservation of momentum

• ED propulsion generates thrust without consuming propellant

• ED propulsion can provide unlimited delta-V
Terminator Tape™

Affordable, Lightweight, End-of-Mission Disposal Module for Orbital Debris Mitigation

- Deploys conducting tape at end-of-mission, gravity gradient stabilized
  - Works regardless of whether its deployed up or down
- Generates electrodynmaic and aerodynamic drag to enable de-orbit within 25 years
- Bolt-on interface with pass-throughs for solar cells
- CubeSat and MicroSat modules available

MicroSat Terminator Tape

CubeSat Terminator Tape
EDTs Enable Deorbit Mass Savings

- Electrodynamic drag tether does not consume propellant to induce thrust
- EDTs can meet end-of-mission disposal requirements with mass penalty of 1-3%
- Chemical rocket stages require 5-20% mass penalty
- Unlike rockets, EDT does not require host spacecraft power and ADCS system to be functional

Terminator Tape Lowers Mass Impact of End-of-Life Disposal
=> More Mass for Payloads & Fuel for Longer Operations
Cubesat Terminator Tape

Deployment Successfully Demonstrated In Microgravity
Electrodynamic Propulsion
ED Orbit Modification & Limits

- Magnetic field strength and direction varies over each orbit
- Electrodynami forces vary in magnitude and direction over each orbit
- Electrodynami forces have components both:
  - In-plane (orbit raising/lowering)
  - Out-of-plane (inclination change)
- Tether current can be modulated over one or more orbits to change all six orbital elements
- Orbit raising/lowering most effective in low & moderate inclination (>70°) orbits
- Inclination change most effective in high inclination orbits
- Useful altitude range: ~300 km to ~2500 km
  - Potentially higher with active current contactor technologies ("vacuum electrodynamics")
ED Propulsion Performance

- ED Tethers can “escape the rocket equation” and provide BOTH high thrust-to-power AND extremely high specific impulse

- Enable missions requiring large total $\Delta V$ to be performed by systems with small wet mass
Momentum-Exchange Propulsion

Nano-THOR

Low-Cost Launch of CubeSats to Deep Space
NanoTHOR CONOPS

- Nanosat & NanoTHOR ride as secondary payloads on GEO satellite launch
- NanoTHOR uses slender, high-strength tether to transfer stage’s orbital energy to the nanosatellite

1. NanoTHOR & NanoSat ride as secondary payloads on GEO launch
2. Upper stage releases primary payload into GTO
3. NanoTHOR retracts tether partially to increase rotation rate
4. NanoSat releases from tether, at GTO perigee, injecting NanoSat into Earth Escape Trajectory
5. NanoTHOR releases tether at apogee; tether re-enters half an orbit later

www.tethers.com
Tether Spin-Up in GTO

- Deploy tether over 2 orbits at \(~50\) cm/s
- Vary deployment rate so that tether is \(~30°\) behind vertical when approaching perigee
- Gravity gradient provides torque to get tether spinning
- Retract tether at \(~25\) cm/s to increase spin rate

We can use tether reeling in the Earth’s gravity well to spin up the tether
Momentum-Exchange/Electrodynamic-Reboost (MXER) Tether

- Rotating tether picks payload up from low-LEO or a suborbital launch vehicle & tosses it to GTO
- System uses electrodynamic thrusting to restore its orbital energy
- Greatly reduces launch vehicle size and cost, or increases payload capacity of launch vehicle
- MXER Launch Assist could make single-stage RLV system viable
MXER Tether Serves Multiple Exploration Missions

- Reusable In-Space “Upper Stage”
  - LEO to GEO
  - Lunar Base Supplies
  - Interplanetary Injection

2-5 fold reduction in launch costs
MXER Tether launch assist may enable single-stage to orbit
Terrestrial Spin-Off Applications

Space Tether Deployment Technology Applied to Planetary Exploration

High Power and Tension Winch for MXER Tether System Applications

Sensor Towing System for UAVs

MAST CubeSat Mission Space Tether Inspection Technology

Optical Tether Dispensers for Underwater Communications & Mobile Robots

Antenna Tower & Bridge Guy Wire Inspection Tool
**Sunmill™ Deployable Solar Array**

- **Deployable Solar Array**
  - 80W Peak power and 49W OAP BOL
  - Panels utilized volume outside of 10x10cm CubeSat
  - Canfield joint carpal gimbal for panel deployment and pointing

- **Key Technologies**
  - Lightweight, stiff, carbon fiber panels
    - Power Density of 92 W/kg
    - High Panel Stiffness
  - Gimbal provides hemispherical pointing

- **SWaP**
  - Size: 2.35U remaining for bus & payload
  - Weight: Panels: 0.95kg, Gimbal: 0.15kg
    - Total: 1.1kg
  - Power: Gimbal consumes 1W maximum
PowerCube provides an enabling set of capabilities: Power, Propulsion and Pointing Control for CubeSats

PowerCube is a 1U module that provides:
- 80 W Peak, 50 W OAP
- $\Delta V=100$ m/sec (for 3kg 3U easily scalable)
- 500 $\mu$Ns bit-impulse, appropriate for attitude control
- Precision pointing of payloads using gimbal and PowerCube as reaction mass

 Enables high-performance, agile CubeSat missions in Earth orbit and beyond
Lightweight Robotic Arm

- For use with nanosats and CubeSats
- 11 DOF, 2m dia. hemispherical workspace
**Technology:**

- VSRS effort is developing fundamental technology for additive manufacturing with polymer-entrained metals to fabricate multi-functional structures with integral radiation shielding
- Combines high-Z/low-Z materials for optimal shielding-per-mass
  - ≥ 55% mass savings over Al for simple enclosures
  - > 80% mass savings with spot shielding
- Additive manufacturing enables complex geometries and in-part variation of material properties to minimize mass of shielding
- Enables rapid and low-cost fabrication of a wide range of radiation shielding solutions:
  - Minimum-mass spot covers and EMI enclosures
  - Structures and MLI with integral radiation shielding
  - Graded-Z shielding

**Phase I Accomplishments**

- Developed compounded PEEK/W and HDPE/W feedstock
- Developed new processes enabling 3D printing with PEEK materials
  - Low-outgassing, high-temperature, high-stiffness polymer
- Demonstrated Fused Deposition Modeling 3DP of prototype electronics cover with Graded-Z spot shielding
  - Responsive Capability: 1 Day from Design to Integration
- Performed analytic modeling of shielding performance
  - Numerical modeling with Geant4 to optimize graded-Z shielding

**Plans for Phase II Effort:**

- Integrate additional compounds for increased material strength as well as thermal and electrical conductivity
- Prototype optimization with Geant4 for the GEO-environment
  - 3D numerical modeling to optimize the internal structure
- Qualification test the VSRS materials for performance:
  - Structural, thermal, outgassing, and conductivity tests
  - Comprehensive irradiation testing representative of the GEO-environment, to compare to on-orbit performance
- Fabricate test instrumentation and print materials to support EAGLE test flight
  - Provide flight heritage for the VSRS materials and technology through data collection and proof of performance on-orbit
SpiderFab

Process for On-Orbit Construction of Kilometer-Scale Apertures

• **Challenge Addressed:**
  – Currently, design, mass, & cost of space systems is driven largely by need to ensure they survive launch loads
  – Size of apertures and structures constrained by need to stow them within available fairings

• **Proposed Innovation:**
  – SpiderFab combines techniques evolved from terrestrial additive manufacturing and composite layup with robotic assembly to enable on-orbit construction of large spacecraft components optimized for the zero-g environment

• **Proposed Effort**
  – Develop architecture and concept designs for SpiderFab system to construct and integrate very large apertures
  – Evaluate ROI of SpiderFab on-orbit construction vs. current SOA deployable technologies
  – Proof-of-concept testing of candidate methods

• **Benefits**
  – SpiderFab constructs space system components with order-of-magnitude improvements in packing efficiency and structural performance, enabling NASA to deploy systems with larger apertures and baselines using smaller, lower cost launch vehicles

• **Payoff**
  – SpiderFab on-orbit construction will enable NASA science and exploration missions to collect and distribute data products with higher bandwidth, higher resolution, higher signal-to-noise, and lower life-cycle cost

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**Schedule**

Qtr 1 2012  |  Qtr 2 2012  |  Qtr 3 2012  |  Qtr 4 2012  |  Qtr 1 2013  |  Qtr 2 2013  |  Qtr 3 2013

Develop Architecture and Concept Design

Evaluate ROI for NASA Missions

SpiderFab Multi-Material Proof-of-Concept

Technology Maturation Plan

Interim Status Review

Write Final Report

Project Management and Reporting

Interim Reporting

Final Report Deliverables
Summary

- Space tethers can provide propellantless propulsion to enable large total-ΔV missions with very low mass requirements
- Electrodynamic tethers can generate thrust at Isp’s of 50,000-200,000 sec. with thrust-to-power competitive with EP thrusters
- Momentum-Exchange/Electrodynamic-Reboost tethers can act as fully-reusable in-space upper stages to achieve dramatic reductions in mission launch costs
- Contrary to popular belief, most tether missions HAVE BEEN SUCCESSFUL
  - Those that did not succeed did so due to failures of engineering processes, not due to fundamental physics
- Tethers are an emerging ‘high-risk, high-payoff’ technology that can enable sustainable space exploration architectures
Advanced Propulsion, Power, & Communications
For Space, Sea, & Air