Space Tethers
Technology Status and The Way Forward

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Definitions

- **Space Tether:**
  - Long, thin cable or wire deployed from a spacecraft

- **Gravity Gradient:**
  - Aligns tether along local vertical and tensions the tether

- **Electrodynamic Tether (EDT):**
  - Conducting tethers can create propulsive forces through Lorentz interactions between currents in the tether and the Earth’s magnetic field

- **Momentum-Exchange (MXT):**
  - High-strength tethers can act as a ‘sling’ to enable transfer of orbital momentum from one spacecraft to another

- **Formation Flight Tether (FFT):**
  - Tethers can constrain multiple spacecraft to fly in formation without expending propellant
Space Tethers: Cross-Cutting, Game-Changing Benefits

Tether propulsion enables large $\Delta V$ missions to be performed by re-usable, low mass systems.

- **Electrodynamic Tether Orbit-Raising and Repositioning**
- **Momentum-Exchange Launch-Assist & Orbit Transfer**
- **Capture & Deorbit of Space Debris**
- **Formation Flying for Long-Baseline SAR & Interferometry**
- **Rendezvous with and remove many objects with small system**
- **Precise & variable long baselines without propellant**
- **Perpetual stationkeeping without resupply costs**
- **Fully-Reusable In-Space Upper Stage**
ED Tethers Can Provide High Thrust (for EP) AND High Isp

Tethers Can Enable Small Systems to Perform Missions Requiring Very High Total ∆V
Alignment with Non-NASA and Non-Aerospace Needs

**Commercial Space:**
- ED tethers can provide cost-effective end-of-mission de-orbit for orbital debris mitigation
- 2-10X cost reductions for launch of satellites
- Re-usable in-space infrastructure for sustainable space program

**Defense:**
- Launch cost reductions for deployment of LEO, MEO, & GEO assets
- Maintain large baselines for high performance missions with lower system mass
- ED tethers can enable game-changing capabilities for certain missions

**Environment:**
- Tethers can enable cost-effective remediation of both orbital debris and radiation belt environments

**Terrestrial Energy:**
- MX Tether “Upper Stage” could enable the dramatic launch cost reductions needed to make space-based solar power economically viable

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Alignment with Non-Aerospace Needs:
Example Terrestrial Spin-Off Applications

- Space Tether Deployment Technology
- Optical Tether Dispensers for Underwater Communications & Mobile Robots
- Momentum-Exchange Tether Technology
- Sensor Towing System for UAVs
- MAST CubeSat Mission Space Tether Inspection Technology
- Antenna Tower & Bridge Guy Wire Inspection Tool
## Technical Risk: Prior History

<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  
• Tethered capsules set in rotation | + Successful deployment and stable rotation                                  |
| 1966 | Gemini-12     | Dynamics                    | • 30-m tether between capsules  
• Tethered capsules set in rotation  
• 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 contactors at both ends  
• Did not measure thrust | + 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 |
| 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 amperic-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  
+ “Pushing on a rope” deployment method resulted in unexpected dynamics, experiment terminated early |
| 1999 | ATEX          | Dynamics                    | • Tape tether deployed with pinch rollers | |
| 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

www.tethers.com
<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>
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<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
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
### Key Technologies Identified by AIAA Space Tethers Technical Committee:

<table>
<thead>
<tr>
<th>Technology Element</th>
<th>EDT</th>
<th>MXT</th>
<th>FFT</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>Stable Deployment of Tether</td>
<td></td>
<td></td>
<td></td>
<td>Demonstrated by PMG, TSS-1 and -1R, SEDS, and TIPS missions</td>
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<tr>
<td>Tracking and Prediction</td>
<td></td>
<td></td>
<td></td>
<td>Not yet demonstrated</td>
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<tr>
<td>M/OD &amp; AO-Survivable Tether</td>
<td></td>
<td></td>
<td></td>
<td>TIPS demonstrated &gt;10-year survival of non-conducting tether; Not yet demonstrated for conducting tether</td>
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<tr>
<td>Tether Retrieval</td>
<td></td>
<td></td>
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<td>Successful retrieval demonstrated by TSS-1</td>
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<tr>
<td>Current Transfer with Ionosphere</td>
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<td></td>
<td></td>
<td>Demonstrated by PMG, TSS-1R, T-REX</td>
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<tr>
<td>Orbit Modification</td>
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<td>Not yet demonstrated</td>
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<tr>
<td>Arc-Resistant or Arc-Tolerant Tether</td>
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<td>Not yet demonstrated</td>
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<tr>
<td>Bare Wire Anode Current Collection</td>
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<td>Not yet demonstrated</td>
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<tr>
<td>High Voltage Power System</td>
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<td>Not yet demonstrated</td>
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<tr>
<td>Dynamic Stabilization of Electrodynamic Tether</td>
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<td></td>
<td></td>
<td>Long-term stability not yet demonstrated</td>
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<tr>
<td>Tethered Payload Disturbance Mitigation</td>
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<td></td>
<td>Not yet demonstrated</td>
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<tr>
<td>Power Generation</td>
<td></td>
<td></td>
<td></td>
<td>Basic physics demonstrated; useful power generation not yet demonstrated</td>
</tr>
<tr>
<td>Very High Strength Space Survivable Tether</td>
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<td>Not yet demonstrated</td>
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<tr>
<td>Stable Spin-Up of Tether System</td>
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<td>Not yet demonstrated</td>
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<tr>
<td>Payload Capture</td>
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<td>Not yet demonstrated</td>
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<tr>
<td>Tethered System Retargeting</td>
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<td>Not yet demonstrated</td>
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<tr>
<td>Precision StationKeeping</td>
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<td>Not yet demonstrated</td>
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<tr>
<td>Precise Tether Deployment/Retrieval</td>
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<td></td>
<td></td>
<td>Not yet demonstrated</td>
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<tr>
<td>Robotic Tether Crawler</td>
<td></td>
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<td></td>
<td>Not yet demonstrated</td>
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</tbody>
</table>
Reasonableness for NASA Investment

- Tether community consensus is that the next step is to demonstrate significant controlled orbital maneuvering with an ED tether.
- Tether community is confident it is ready to demonstrate electrodynamic tether propulsion on an operationally-relevant system.
- Validation of tether systems can only be carried out on orbit.
- Because a flight mission is required, government investment is required to enable ED Tethers to progress through the TRL valley-of-death.
- Cost/performance benefit of ED tethers can recover investment within 1-2 operational missions.