Space Tethers
Technology Status and The Way Forward

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Definitions

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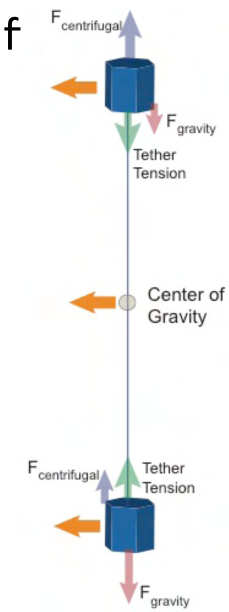
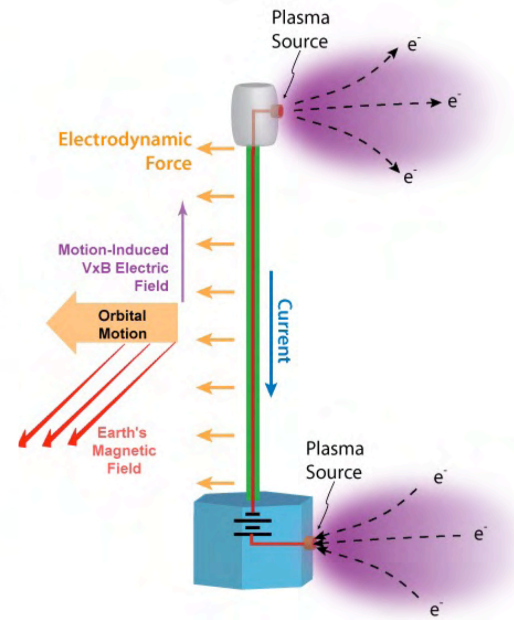
- **Space Tether:**
  - Long, thin cable or wire deployed from a spacecraf
- **Gravity Gradient:**
  - Aligns tether along local vertical and tensions the tether
- **Electrodynamic Tether (EDT):**
  - Conducting tethers can create propulsive forces through Lorentz interactions between currents in the 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

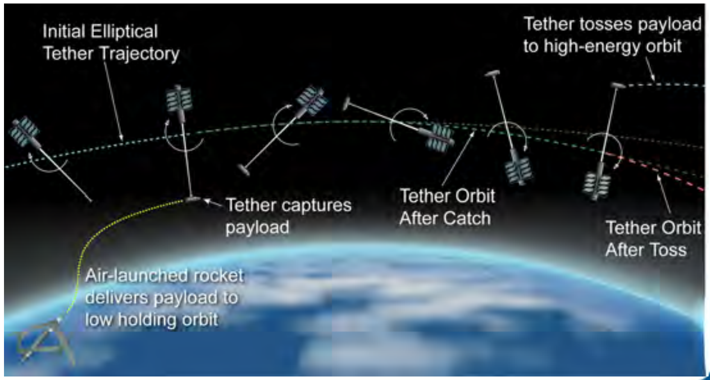
Gravity Gradient



Electrodynamic Propulsion



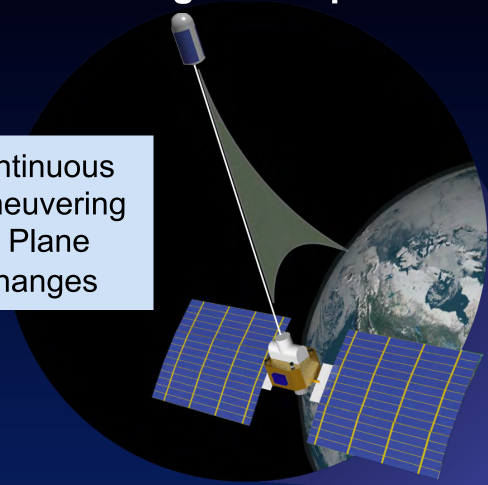
Momentum Exchange



Space Tethers: Cross-Cutting, Game-Changing Benefits

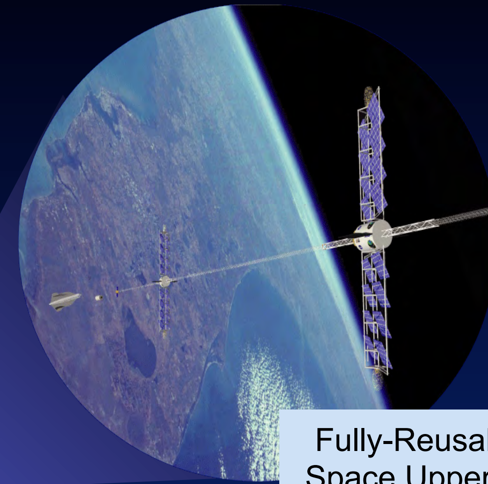
Tether propulsion enables large ΔV missions to be performed by re-usable, low mass systems

Electrodynamic Tether Orbit-Raising and Repositioning



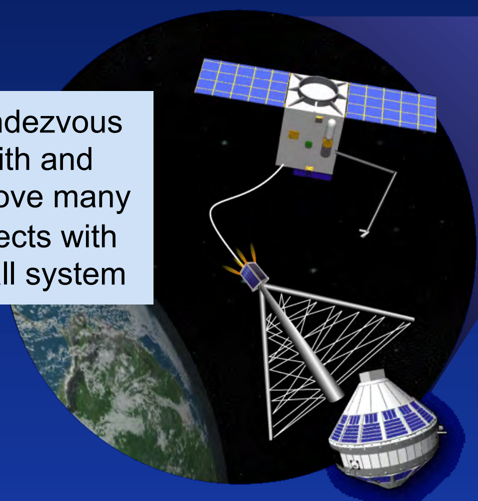
Continuous Maneuvering & Plane Changes

Momentum-Exchange Launch-Assist & Orbit Transfer



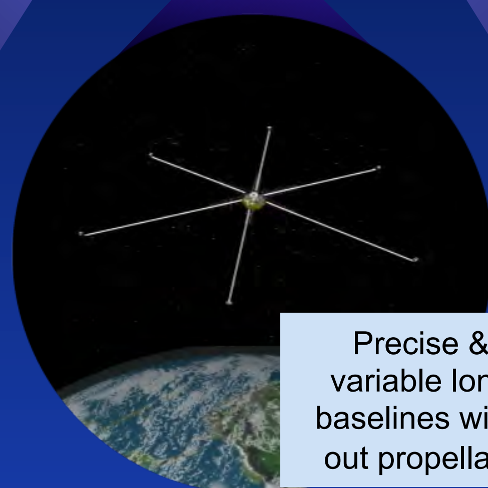
Fully-Reusable In-Space Upper Stage

Capture & Deorbit of Space Debris



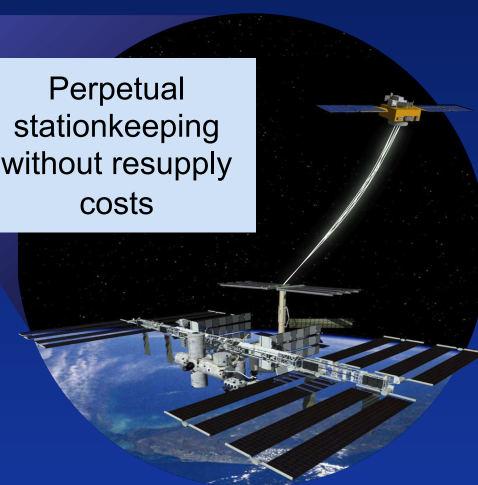
Rendezvous with and remove many objects with small system

Formation Flying for Long-Baseline SAR & Interferometry



Precise & variable long baselines with-out propellant

Drag-Makeup Stationkeeping for LEO Assets



Perpetual stationkeeping without resupply costs

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Electrodynamic Tethers: Performance Characteristics

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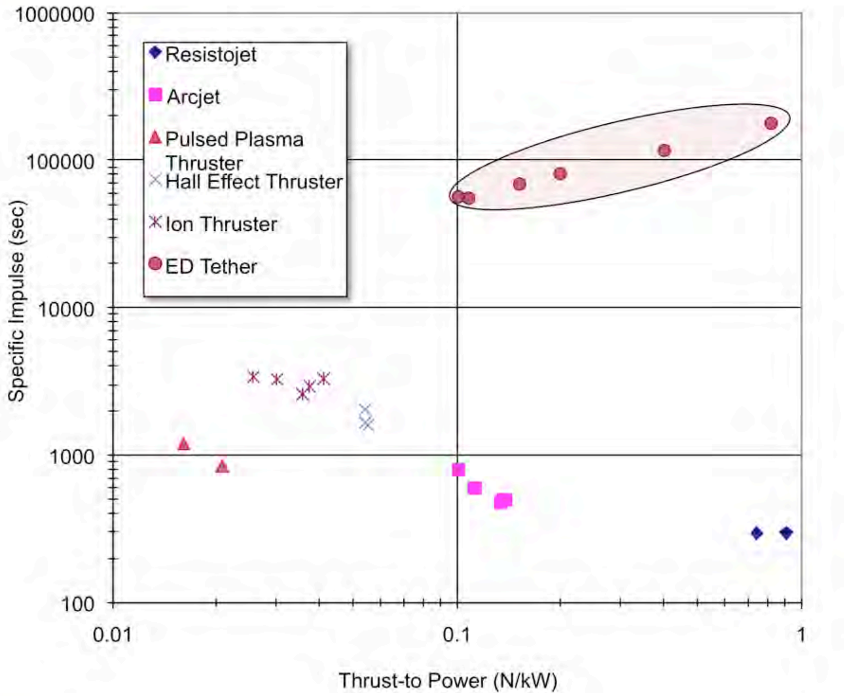
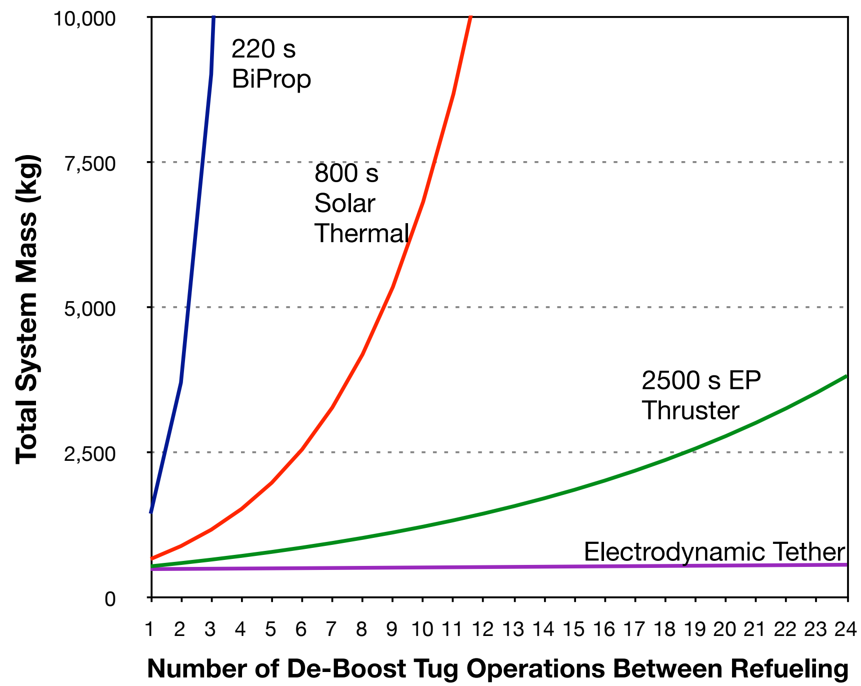
Thrust-to-Power vs Isp



ED Tethers Can Provide
High Thrust (for EP) AND High Isp

System Mass for Orbital Debris Removal Tug

(1 mT OD objects, 10° plane change per object)



Tethers Can Enable Small Systems to Perform Missions Requiring Very High Total ΔV

Alignment with Non-NASA and Non-Aerospace Needs

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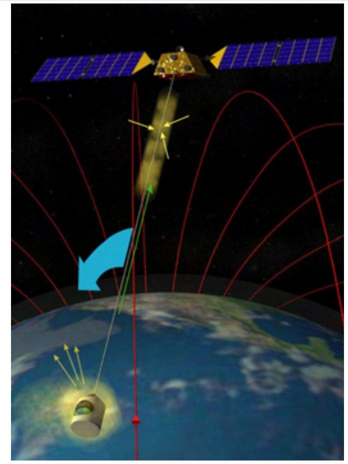
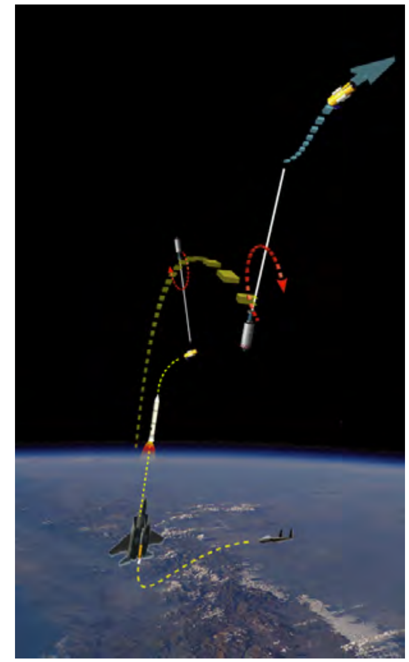
Commercial Space:
- ED tethers can provide cost-effective end-of-mission de-orbit for orbital debris mitigation
- 2-10X cost reductions for launch of satellites
- Re-usable in-space infrastructure for sustainable space program

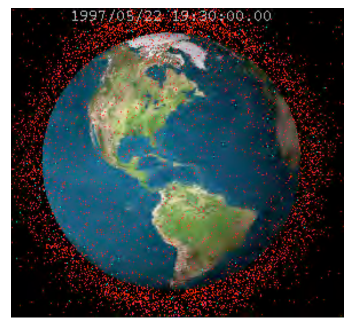
Defense:
- Launch cost reductions for deployment of LEO, MEO, & GEO assets
- Maintain large baselines for high performance missions with lower system mass
- ED tethers can enable game-changing capabilities for certain missions

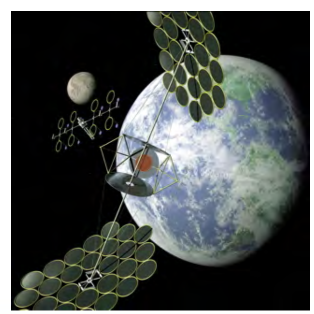
Environment:
- Tethers can enable cost-effective remediation of both orbital debris and radiation belt environments

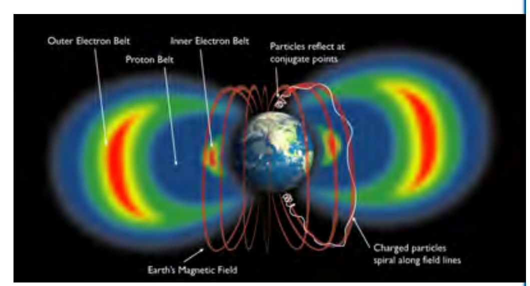
Terrestrial Energy:
- MX Tether "Upper Stage" could enable the dramatic launch cost reductions needed to make space-based solar power economically viable











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

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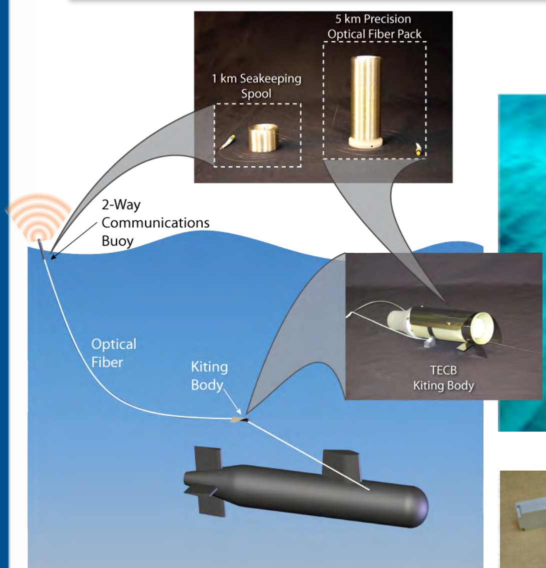
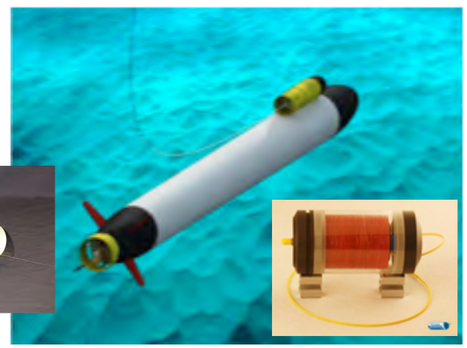
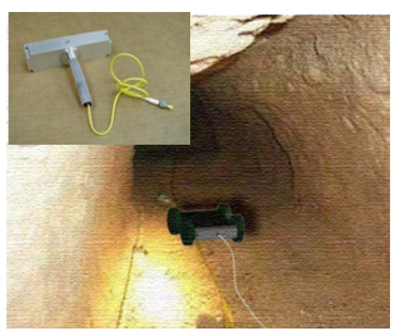
Space Tether Deployment Technology

Optical Tether Dispensers for Underwater Communications & Mobile Robots

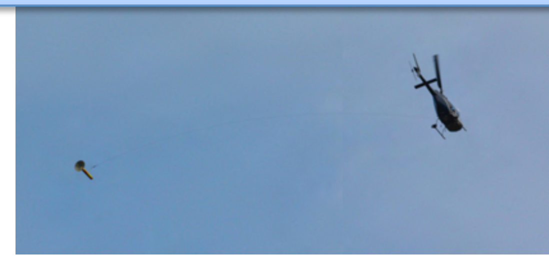






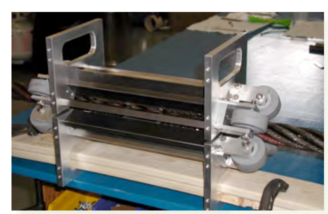
Momentum-Exchange Tether Technology

Sensor Towing System for UAVs



MAST CubeSat Mission Space Tether Inspection Technology

Antenna Tower & Bridge Guy Wire Inspection Tool



Technical Risk: Prior History

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■ = Met All Mission Goals ■ = Did Not Meet All Mission Goals

Year	Mission	Type	Description	Lessons Learned
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 t + 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	+ 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 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

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

80% Failure Rate

Past Space Tether Experiments

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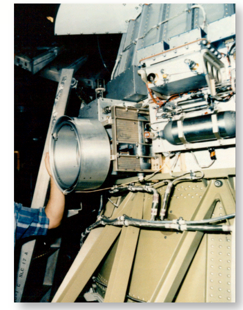
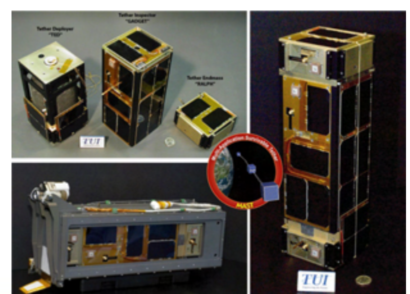
- **Rotating tethered capsule experiments during Gemini missions**
- **Small Expendable Deployer System (SEDS)**
  - SEDS 1: de-orbited a small payload using 20 km tether
  - SEDS 2: demonstrated controlled deployment of a 20 km tether
  - PMG: demonstrated basics of electrodynamic physics using 500 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



Status of Key Technologies and Development Plan

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Key Technologies Identified by AIAA Space Tethers Technical Committee:

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

Reasonableness for NASA Investment

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- 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