TETHERS UNLIMITED

Advanced Propulsion, Power, & Comm. for Space, Sea, & Air

Space Tethers 101

Dr. Rob Hoyt

CEO & Chief Scientist

Tethers Unlimited, Inc.

www.tethers.com

Agenda

Tethers Unlimited
Advanced Propulsion, Power, & Comm
for Space, Sea, & Air

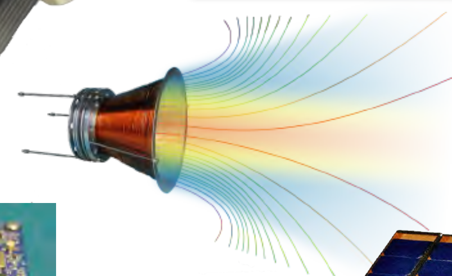
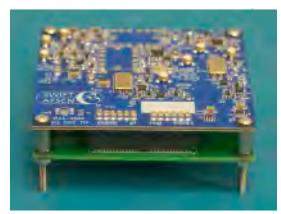
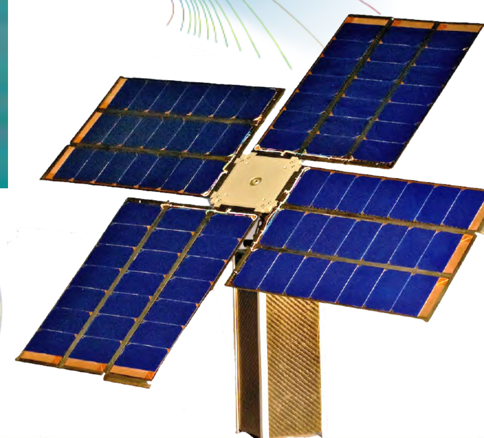
- About Tethers Unlimited, Inc.
- What's a Space Tether?
- History & Status of Tethers
- Space Tether Physics
- Electrodynamic Propulsion
- Momentum Exchange Propulsion

About Tethers Unlimited, Inc.

TETHERS UNLIMITED
Advanced Propulsion, Power, & Comm for Space, Sea, & Air

- **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-picosatellite 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



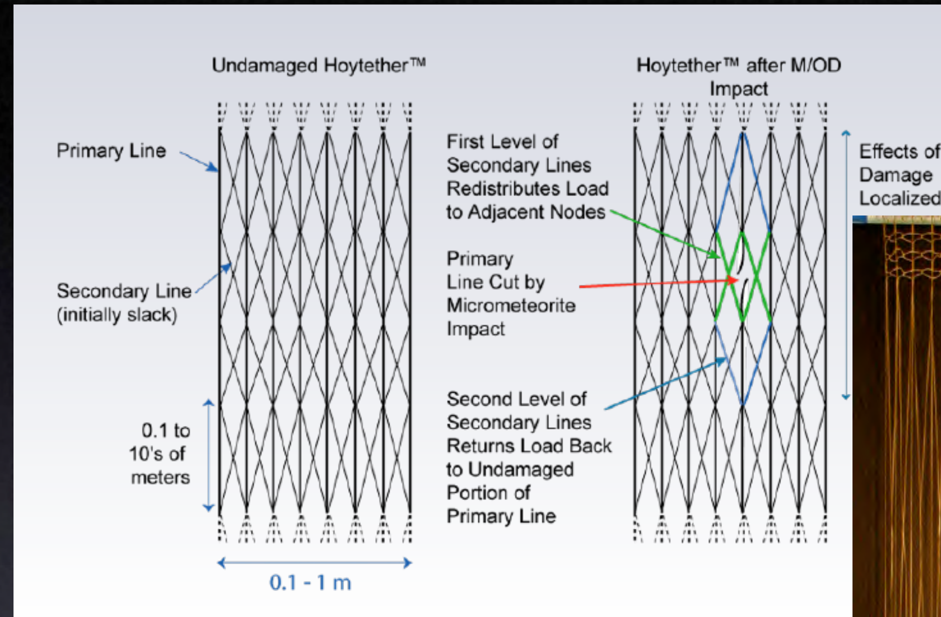

Space Tethers

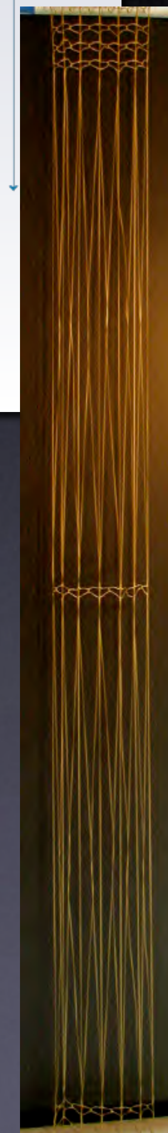
TETHERS UNLIMITED
Advanced Propulsion, Power, & Comm
for Space, Sea, & Air

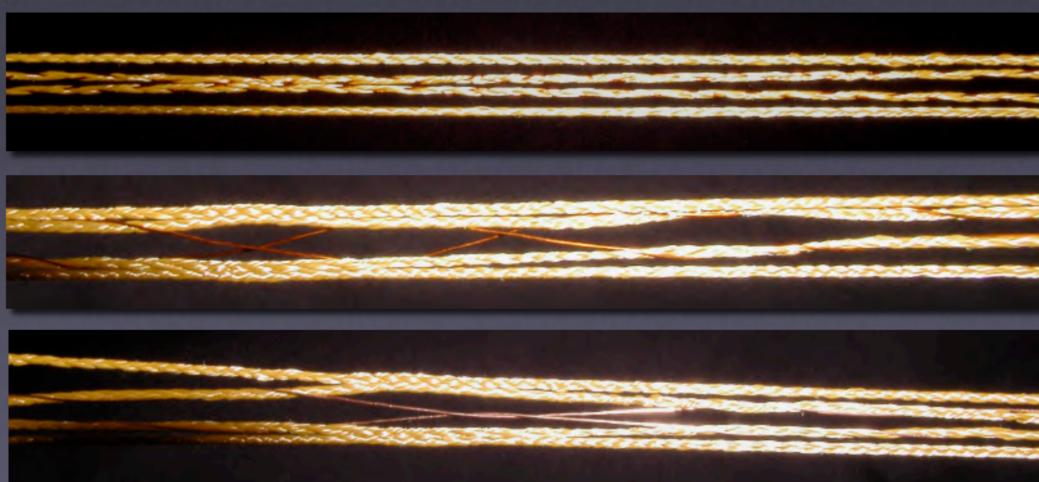
- Long, thin cable or wire deployed from a spacecraft
- High strength tethers can enable momentum transfer from one spacecraft to another
- Conducting tethers can create propulsive forces through Lorentz force interactions with the Earth's magnetic field

High-Strength Space-Survivable Tether

- Materials available today (eg 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



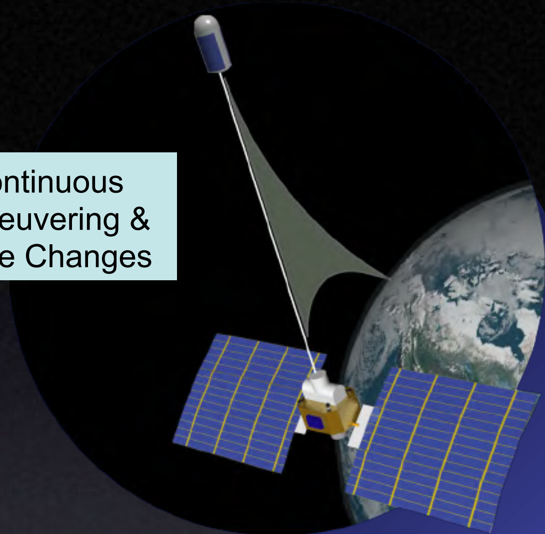




Space Tethers: Cross-Cutting, Game-Changing Benefits

Propellantless propulsion enables **large ΔV** missions with **low mass impact**

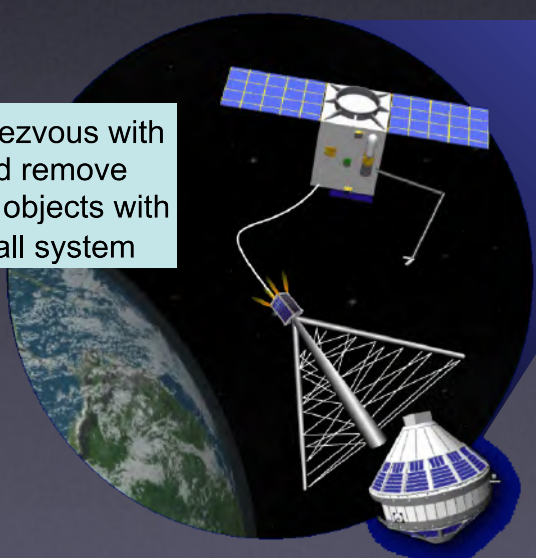
Electrodynamic Tether
Orbit-Raising and Repositioning



Continuous Maneuvering & Plane Changes

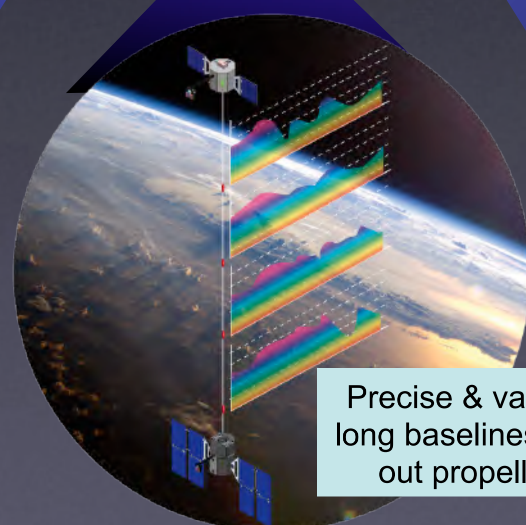
Momentum-Exchange
Launch-Assist & Orbit Transfer

Fully-Reusable In-Space Upper Stage



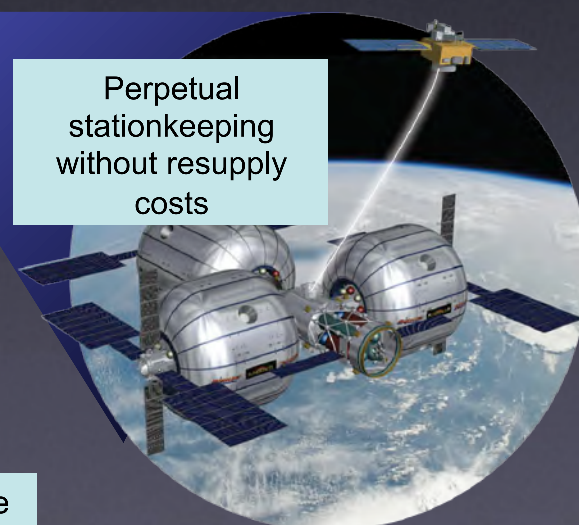
Rendezvous with and remove many objects with small system

Capture & Deorbit of Space Debris



Precise & variable long baselines with-out propellant

Formation Flying for
Multi-Point Science & Long-Baseline Sensing



Perpetual stationkeeping without resupply costs

Drag-Makeup Stationkeeping
for LEO Assets

History & Status of Space Tethers

Space Tethers: Prior Missions

TETHERS UNLIMITED
Advanced Propulsion, Power, & Comm for Space, Sea, & Air

■ = 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

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 of Early Missions

Past Space Tether Experiments

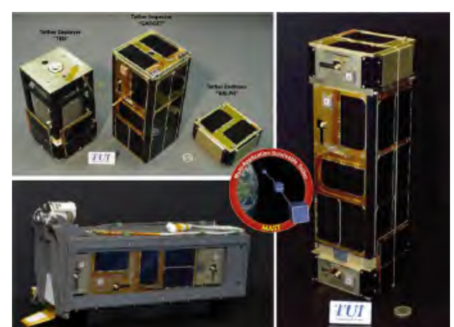
TETHERS UNLIMITED
Advanced Propulsion, Power, & Comm for Space, Sea, & Air

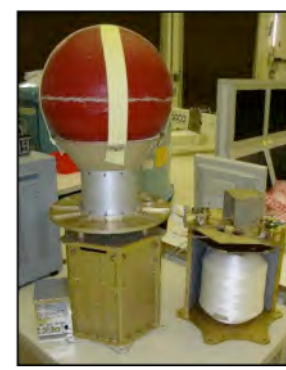
- Rotating tethered capsule experiments during Gemini missions
- Small Expendable Deployer System (SEDS)
  - SEDS 1: de-orbited a small payload using 20 km tether
  - SEDS 2: demonstrated controlled deployment of a 20 km tether
  - PMG: demonstrated basics of electrodynamic physics using 500 m conducting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



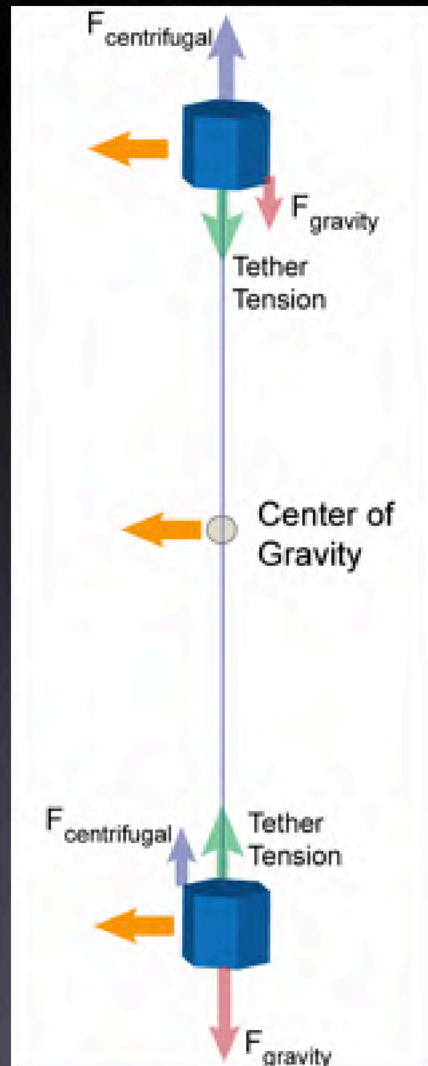


Space Tether Physics

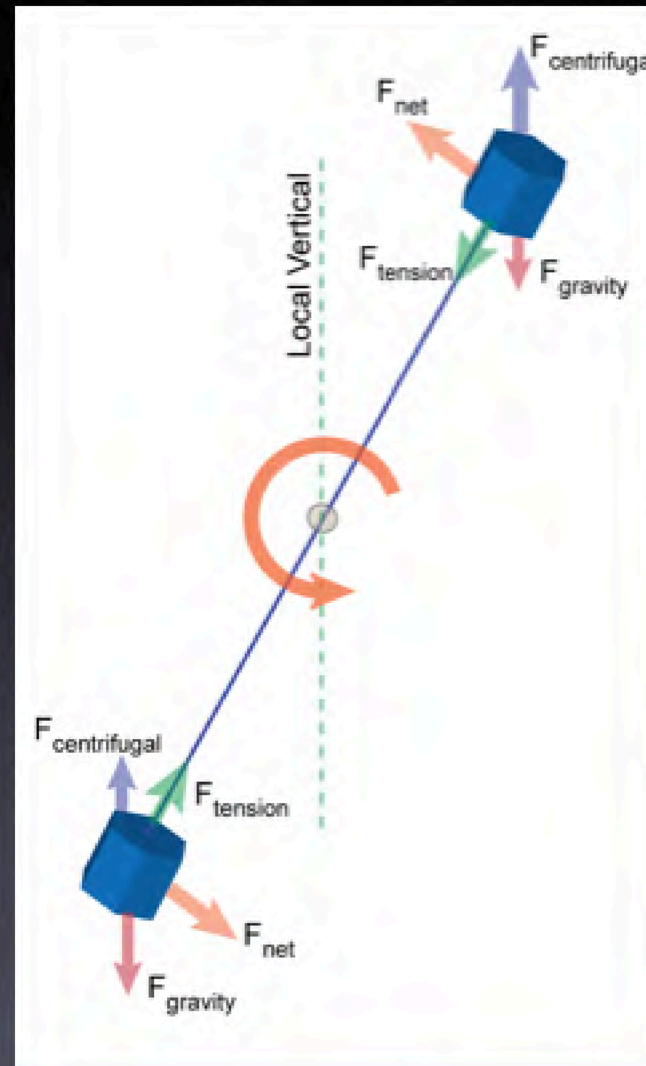
Gravity Gradient

Tethers Unlimited
Advanced Propulsion, Power, & Comm. for Space, Sea, & Air

No Tether



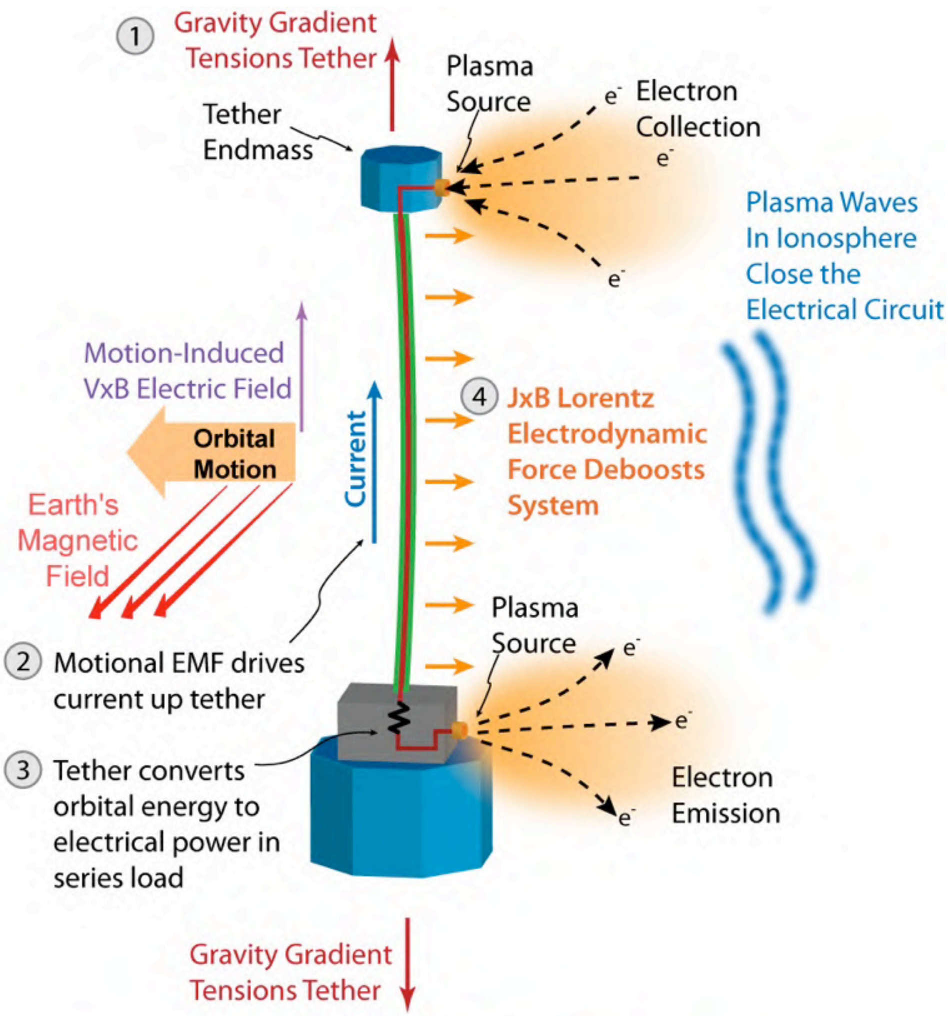
Tether forces satellites to co-orbit at center of gravity's orbital velocity



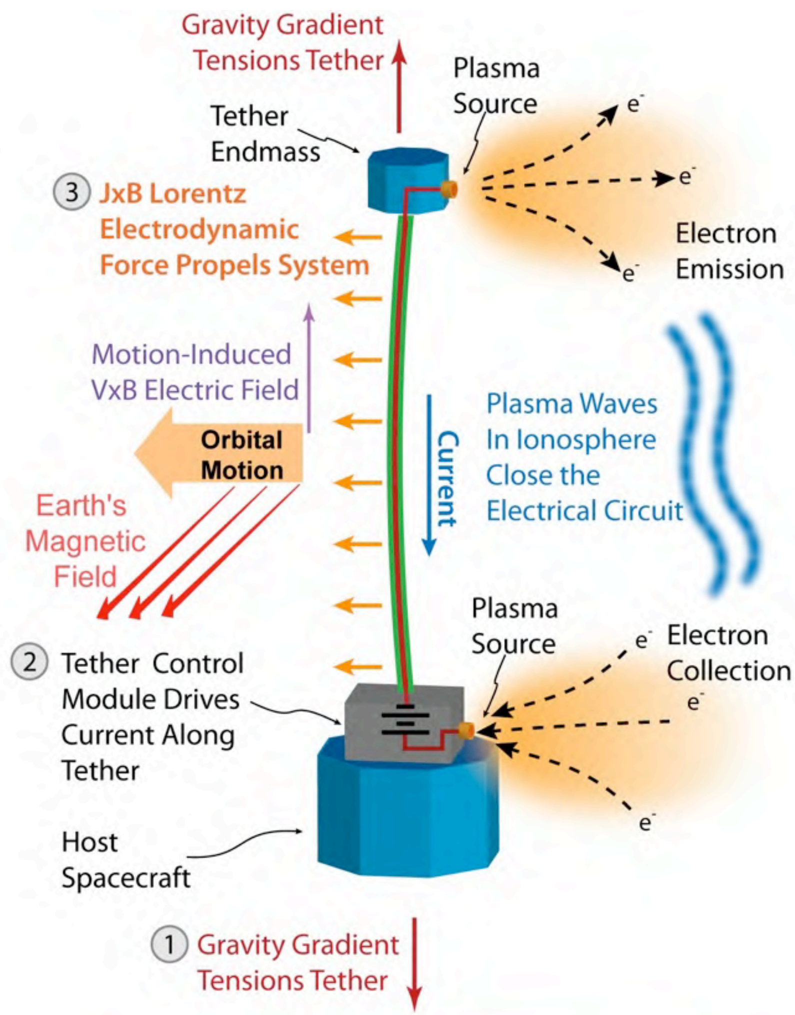
Gravity gradient provides restoring force to align tether along local vertical

Electrodynamic Tether

Deboost/Power Generation



Boost Mode



Electrodynamic Propulsion Fundamentals

TETHERS UNLIMITED
Advanced Propulsion, Power, & Comm. for Space, Sea, & Air

- 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

$$F = J \times B$$

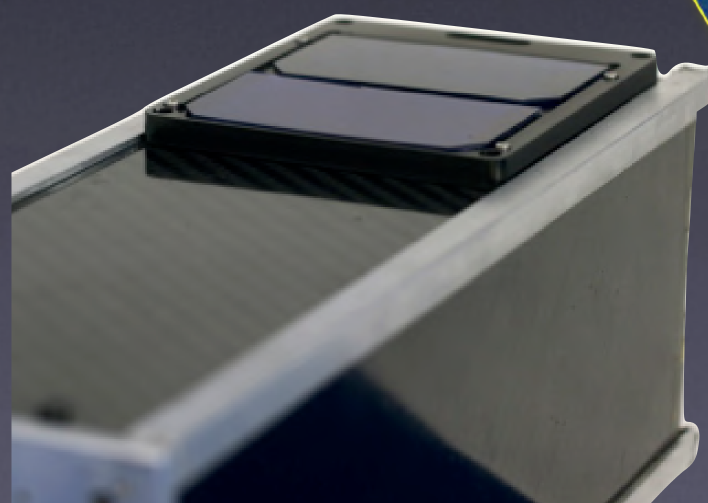
- Same fundamental physics as electric motors & electric generators
- Conducting plasma in ionosphere provides a mechanism for 'closing the current loop'
- The Earth serves as the reaction mass for conservation of momentum
- ED propulsion generates thrust without consuming propellant
- ED propulsion 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 electrodynamic and aerodynamic drag to enable de-orbit within 25 years
- Bolt-on interface with pass-throughs for solar cells
- CubeSat and MicroSat modules available

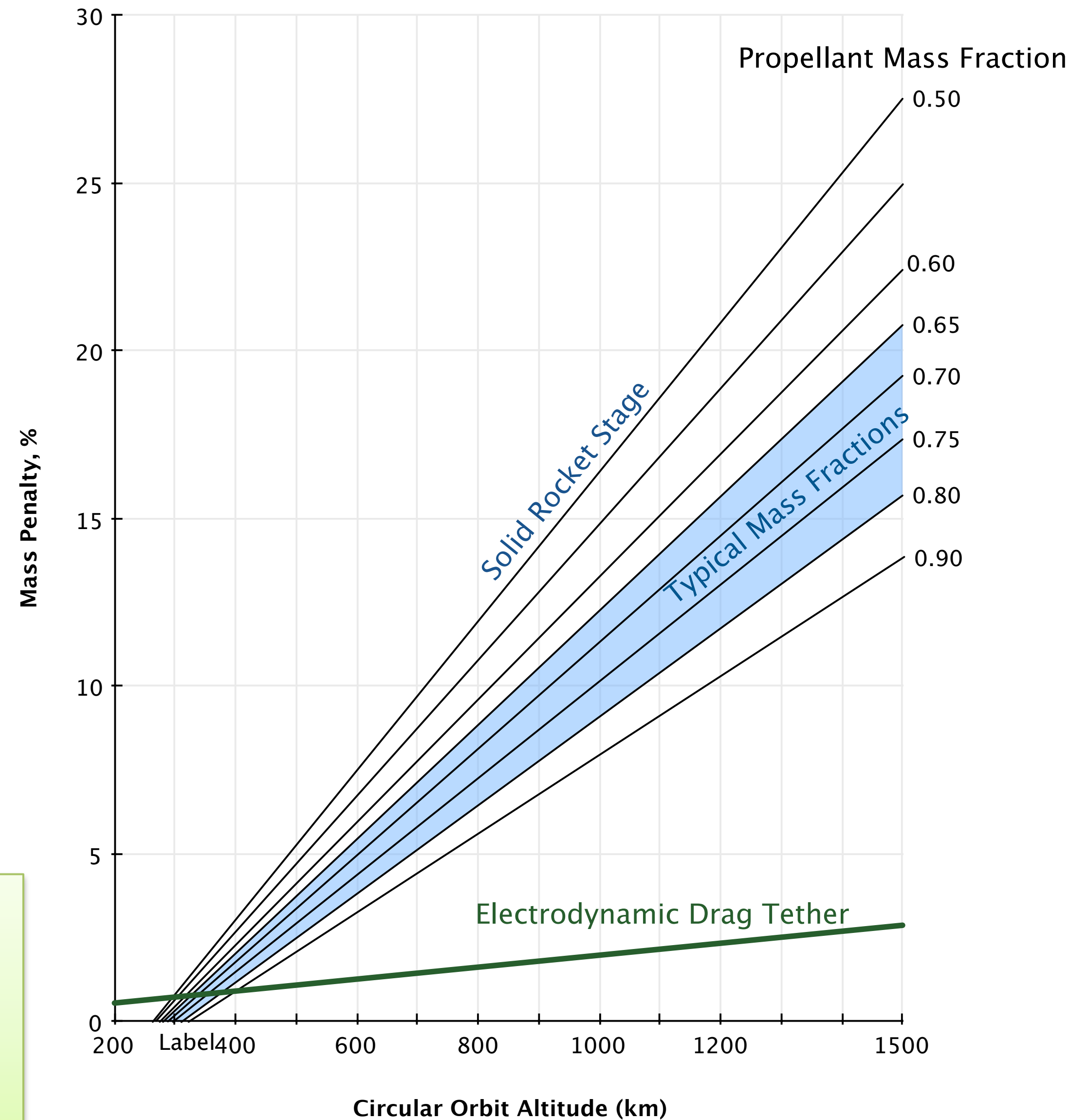
MicroSat Terminator Tape



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

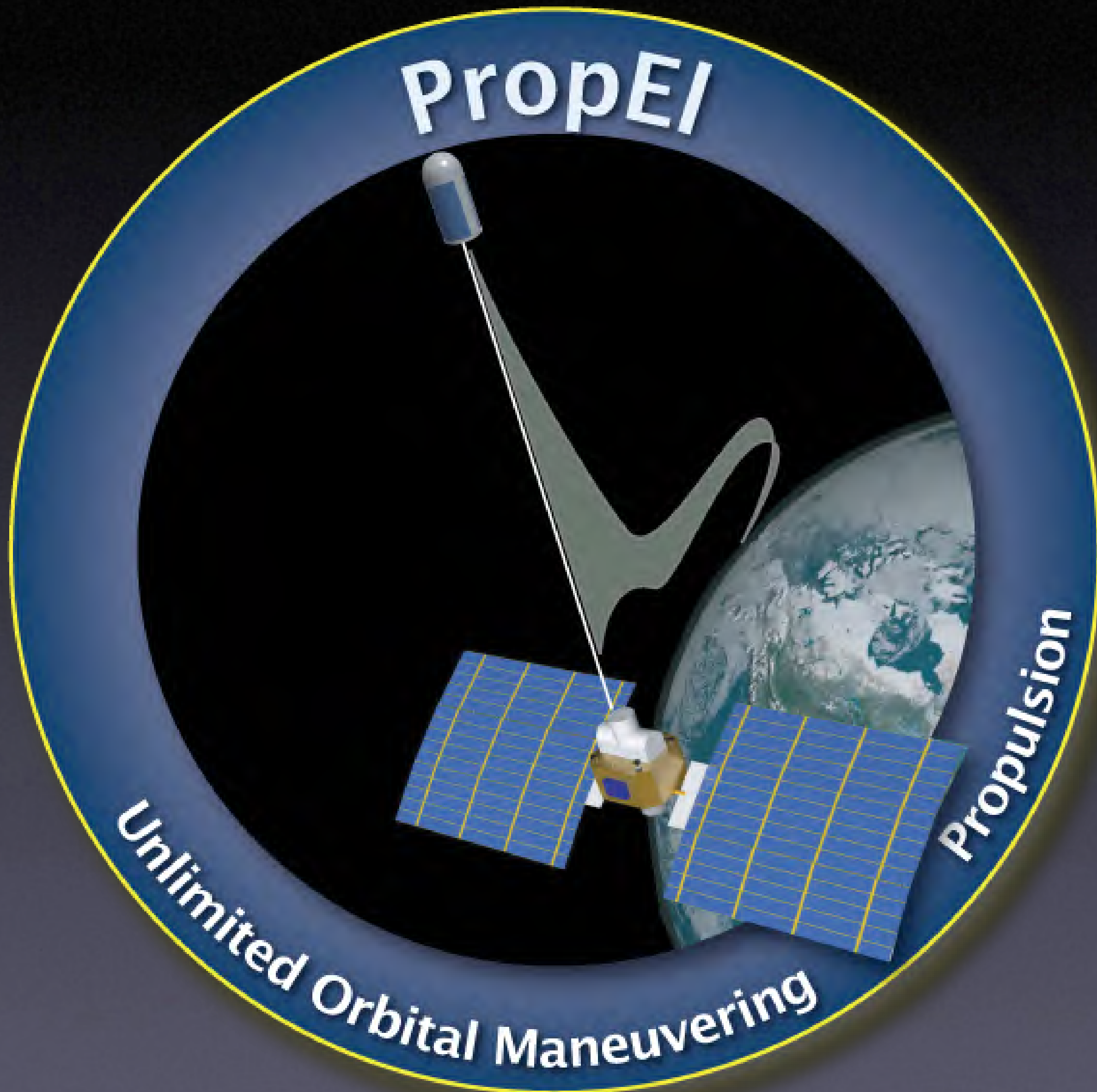
Cubesat Terminator Tape

TETHERS UNLIMITED
Advanced Propulsion, Power, & Comm.
for Space, Sea, & Air

Deployment Successfully Demonstrated In Microgravity

Electrodynamic Propulsion

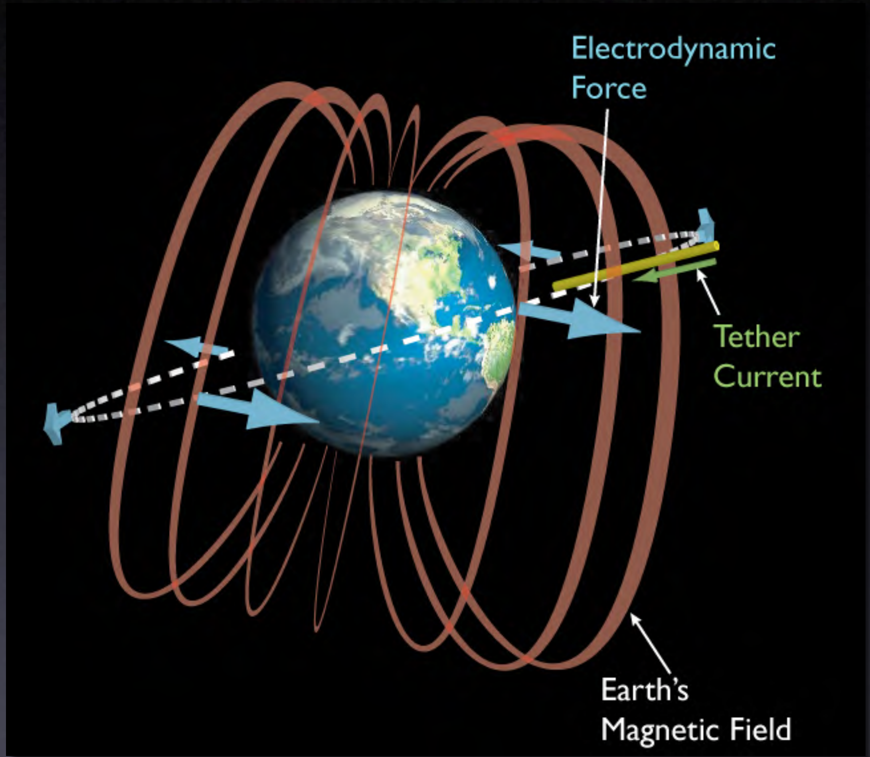
Advanced Propulsion, Power, & Comm
for Space, Sea, & Air



ED Orbit Modification & Limits

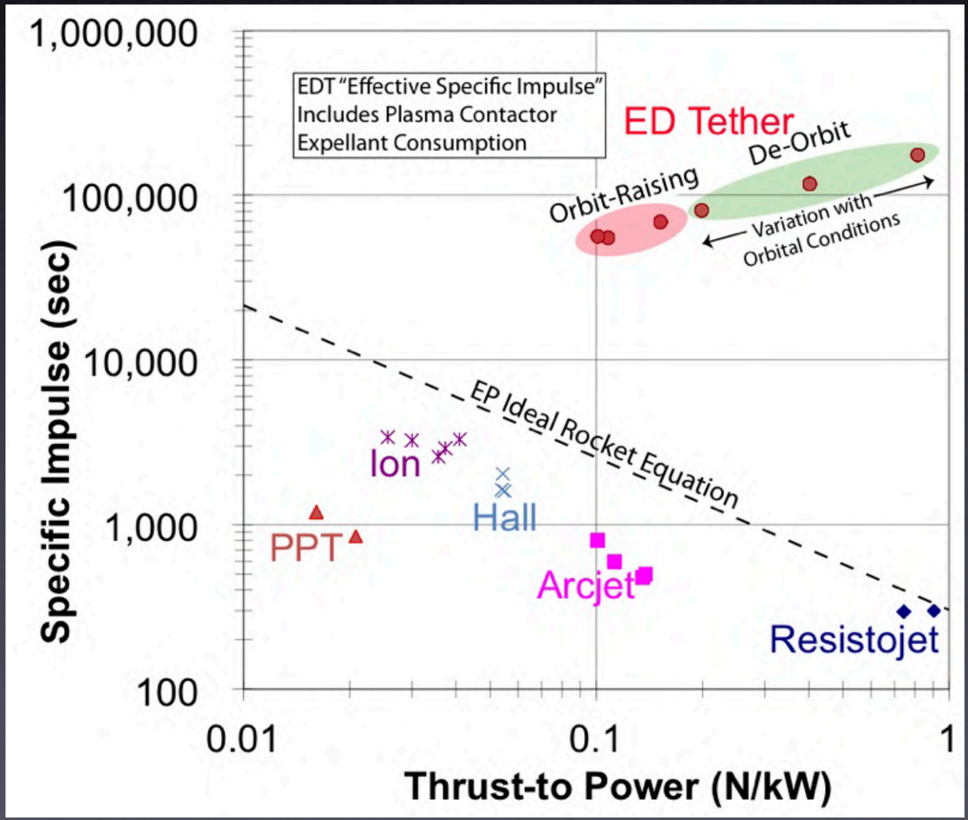
Tethers Unlimited
Advanced Propulsion, Power, & Comm. for Space, Sea, & Air

- Magnetic field strength and direction varies over each orbit
- Electrodynamic forces vary in magnitude and direction over each orbit
- Electrodynamic 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



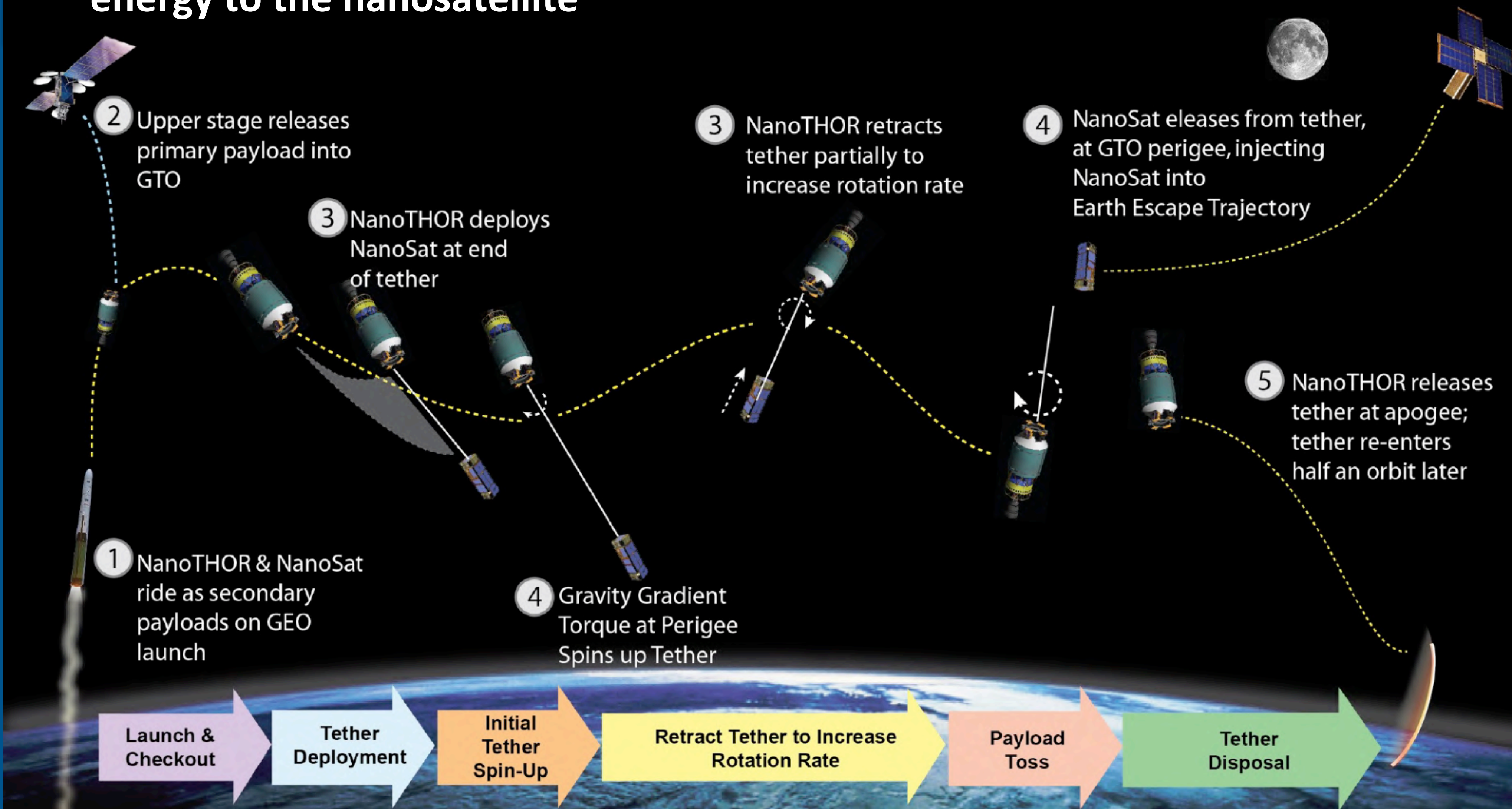
- Enable missions requiring large total ΔV to be performed by systems with small wet mass

Momentum-Exchange Propulsion

TETHERS UNLIMITED
Advanced Propulsion, Power, & Comm
for Space, Sea, & Air

NanoTHOR CONOPS

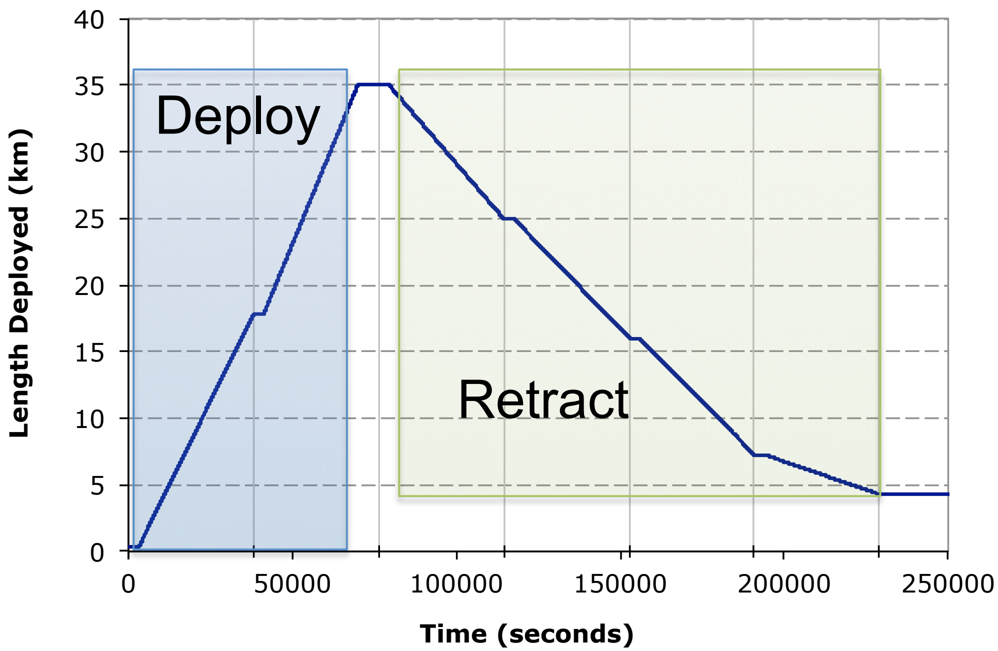
- **Nanosat & NanoTHOR ride as secondary payloads on GEO satellite launch**
- **NanoTHOR uses slender, high-strength tether to transfer stage's orbital energy to the nanosatellite**

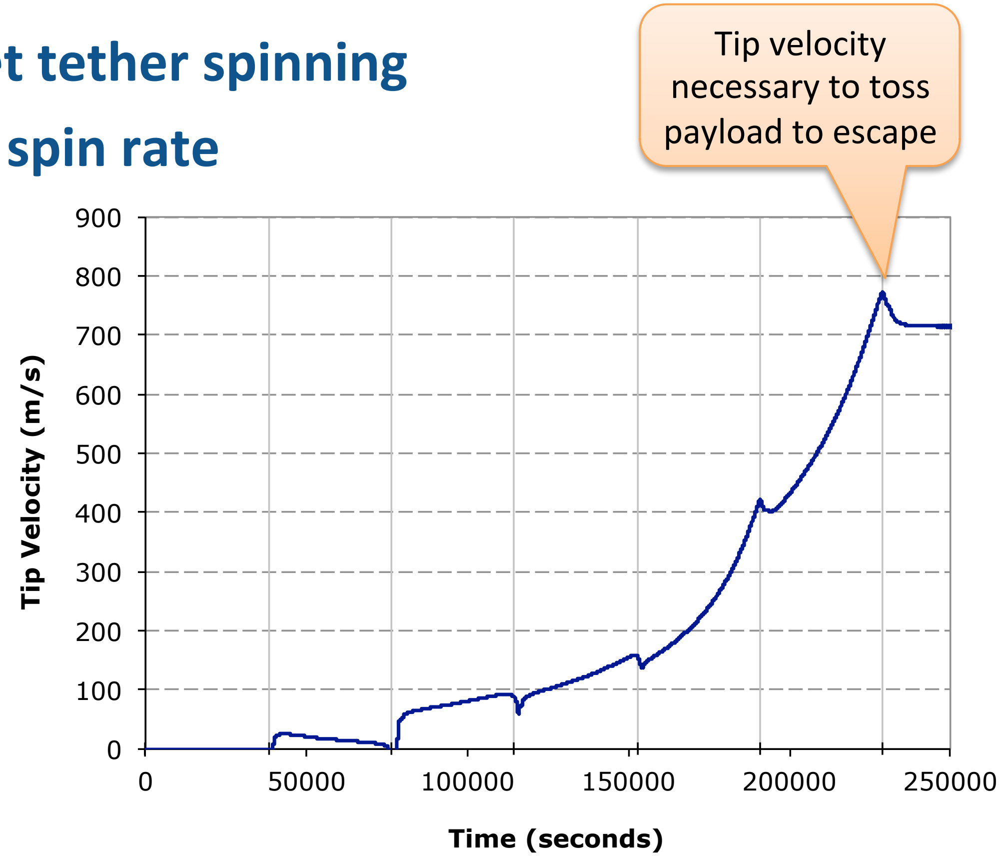


Tether Spin-Up in GTO

TETHERS UNLIMITED
Advanced Propulsion, Power, & Comm for Space, Sea, & Air

- 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

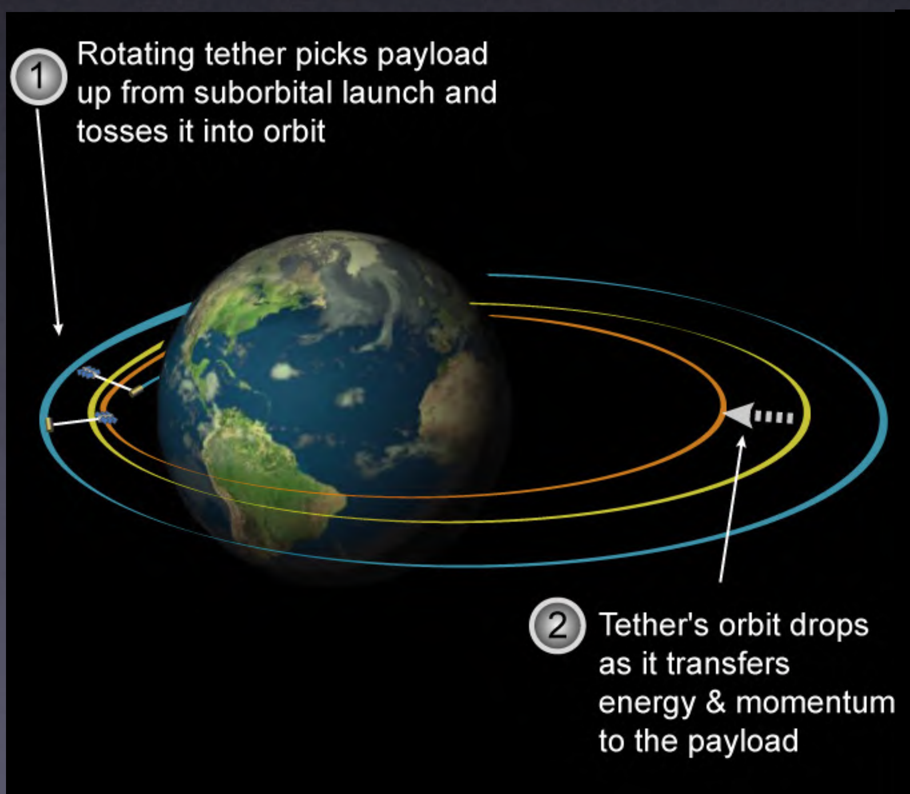


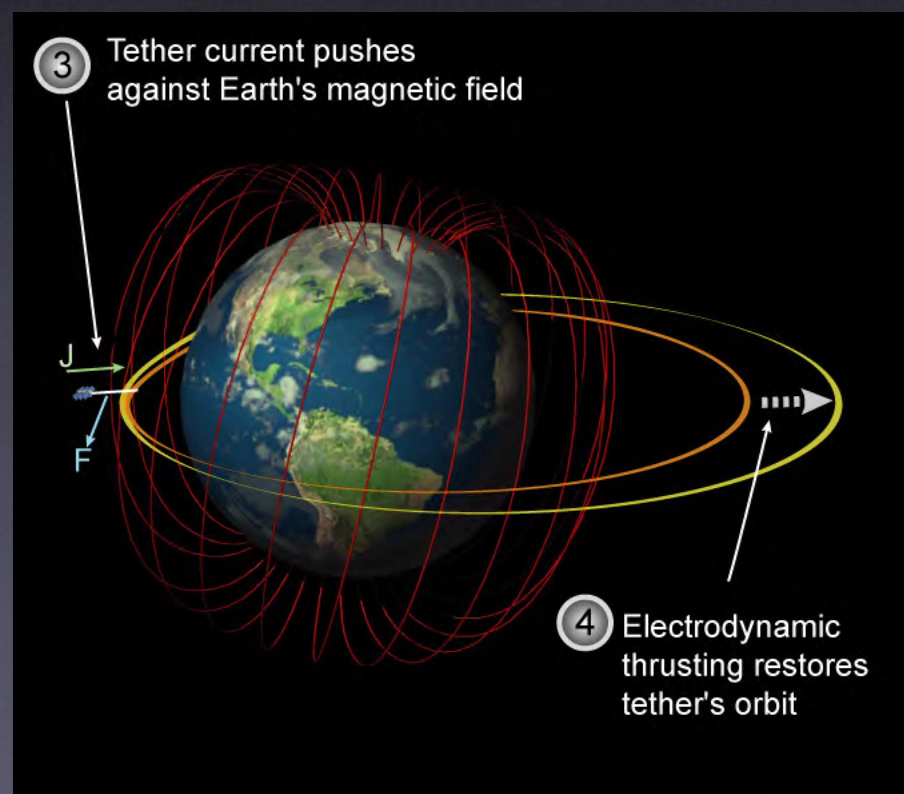


We can use tether reeling in the Earth's gravity well to spin up the tether

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



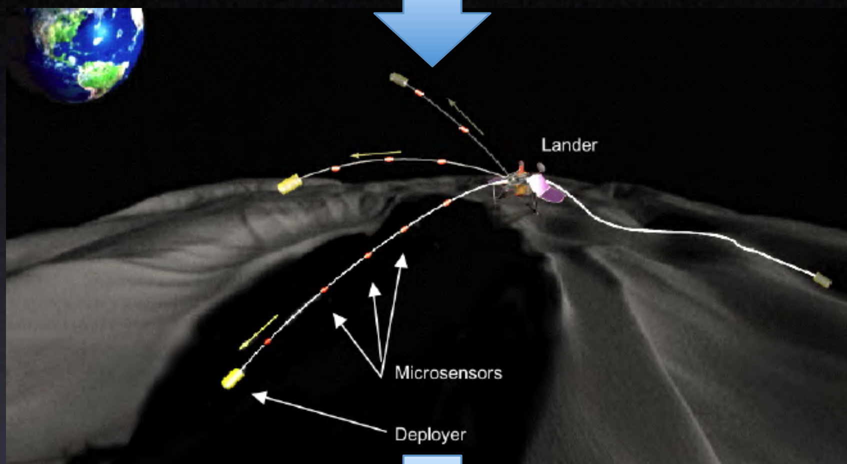


MXER Tether Serves Multiple Exploration Missions

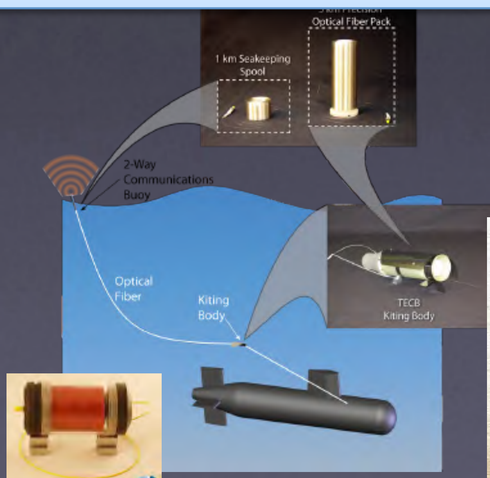
- Reusable In-Space "Upper Stage"
  - LEO to GEO
  - Lunar Base Supplies
  - Interplanetary Injection

Terrestrial Spin-Off Applications

Space Tether Deployment Technology Applied to Planetary Exploration



Optical Tether Dispensers for Underwater Communications & Mobile Robots



High Power and Tension Winch for MXER Tether System Applications

Sensor Towing System for UAVs

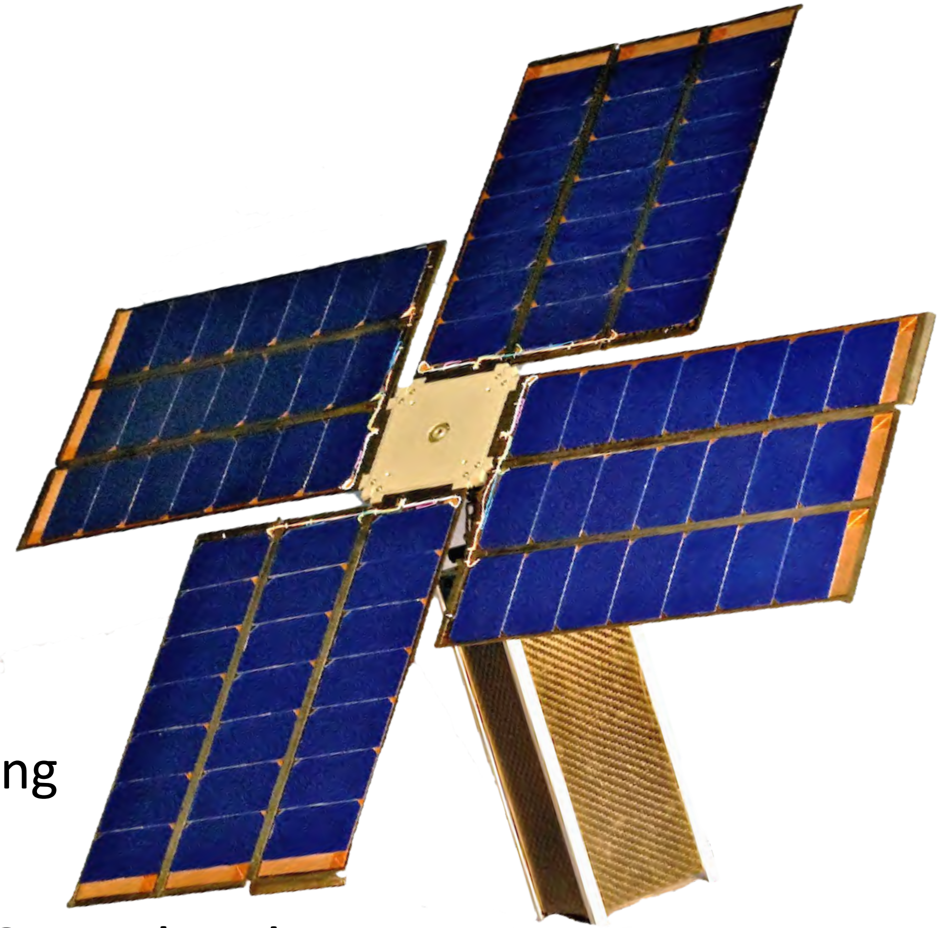
MAST CubeSat Mission Space Tether Inspection Technology

Antenna Tower & Bridge Guy Wire Inspection Tool

Sunmill™ Deployable Solar Array

TETHERS UNLIMITED
Advanced Propulsion, Power, & Comm. for Space, Sea, & Air

- **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 <u>maximum</u>



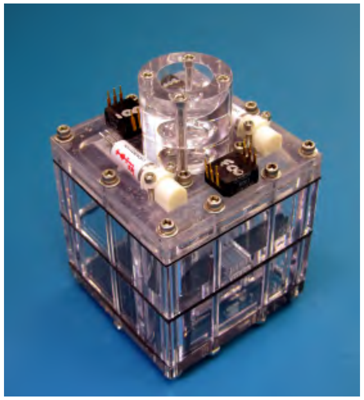
PowerCube provides an enabling set of capabilities: Power, Propulsion and Pointing Control for CubeSats

PowerCube is a 1U module that provides:

- 80 W Peak, 50 W OAP
- ΔV=100 m/sec (for 3kg 3U easily scalable)
- 500 µNs bit-impulse, appropriate for attitude control
- Precision pointing of payloads using gimbal and PowerCube as reaction mass

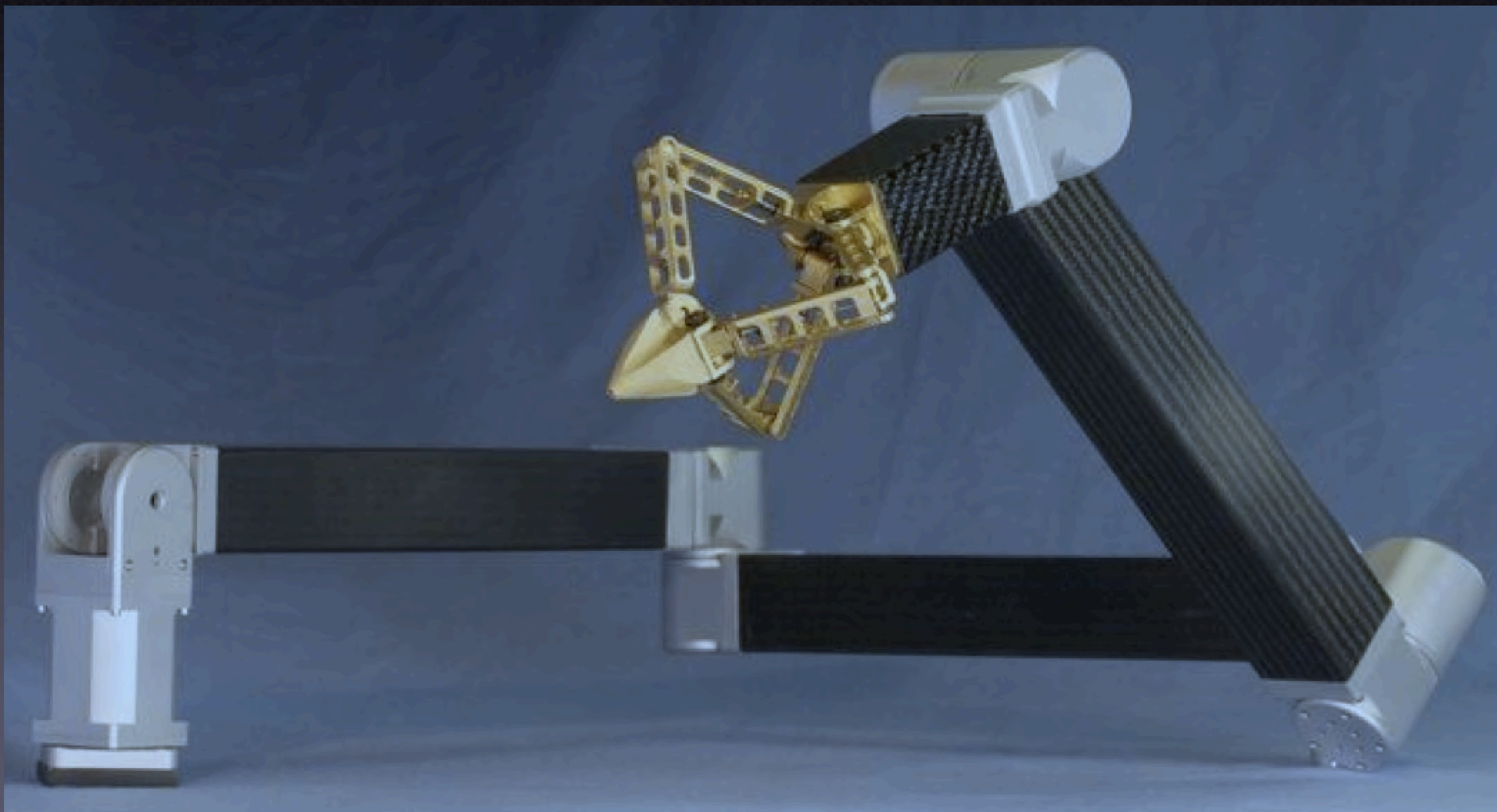
Enables high-performance, agile CubeSat missions in Earth orbit and beyond

Phase I SBIR Prototype



Lightweight Robotic Arm

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



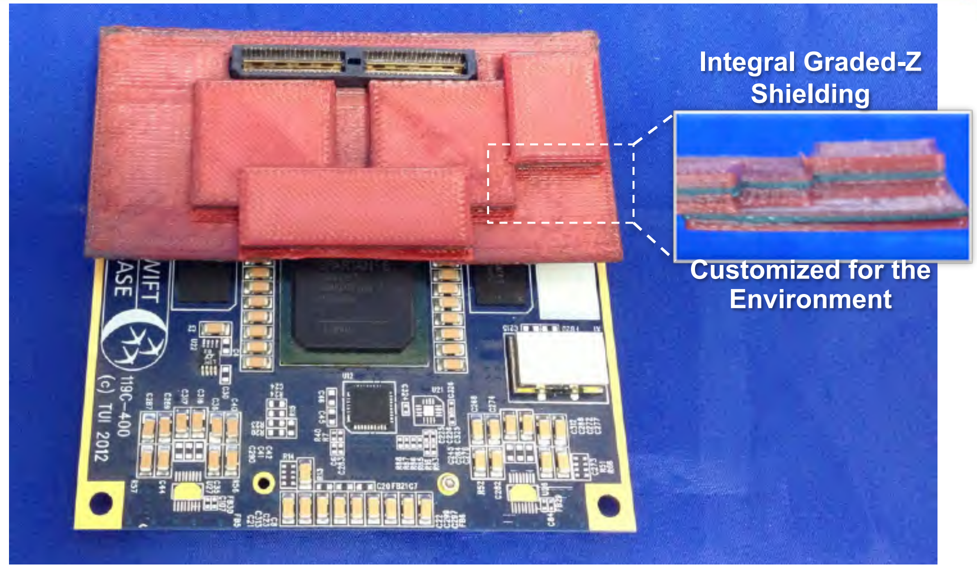
Versatile Structural Radiation Shielding (VSRS™)

Tethers Unlimited, Inc. FA9453-12-M-0336

TETHERS UNLIMITED
Advanced Propulsion, Power, & Comm for Space, Sea, & Air

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



Prototype VSRS Cover with Spot Shielding

VSRS Extends the Lifetime of COTS Components in High-Rad Environments

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

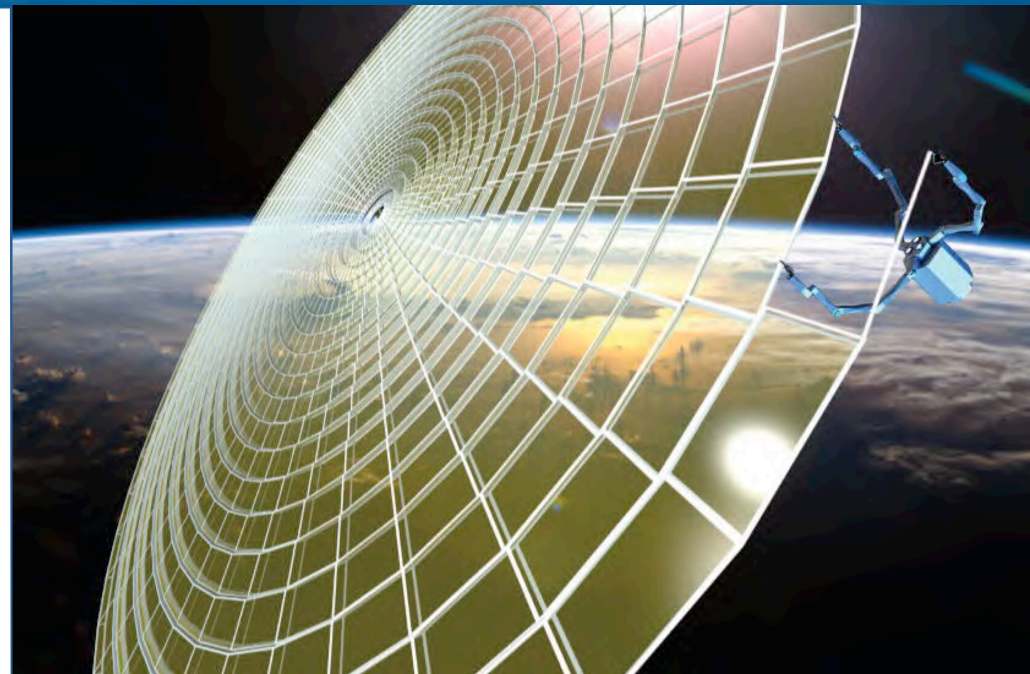
SpiderFab

425-486-0100 info@tethers.com
11711 N. Creek Pkwy S., D113 Bothell
WA 98011 www.tethers.com

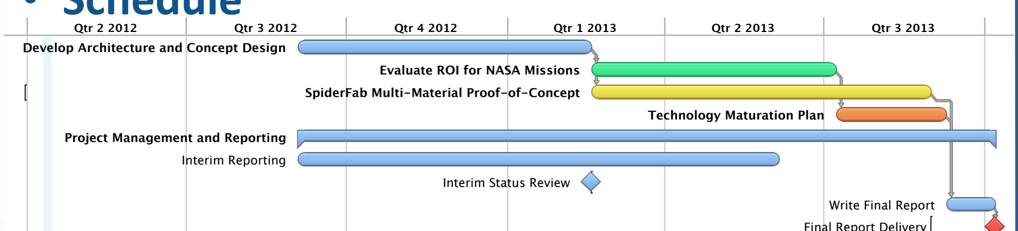
TETHERS UNLIMITED
Advanced Propulsion, Power, & Comm. for Space, Sea, & Air

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
- **Schedule**



- **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

Summary

Tethers Unlimited
Advanced Propulsion, Power, & Comm.
for Space, Sea, & Air

- 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


TETHERS
UNLIMITED
Advanced Propulsion, Power, & Communications
For Space, Sea, & Air