Why Not Space Tethers?

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ABSTRACT

The Tethered Satellite System Space Shuttle missions, TSS-1 in 1993 and TSS-1R in 1996, were the height of space tether technology development. Since NASA’s investment of some $200M and two Shuttle missions in those two pioneering missions, there have been several smaller tether flight experiments, but interest in this promising technology has waned within NASA as well as the DOD agencies. This is curious in view of the unique capabilities of space tether systems and the fact that they have been flight validated and shown to perform as, or better than, expected in earth orbit. While it is true that the TSS-1, TSS-1R and SEDS-2 missions experienced technical difficulties, the causes of these early developmental problems are now known to be design or materials flaws that are (1) unrelated to the basic viability of space tether technology, and (2) they are readily corrected. The purpose of this paper is to review the dynamic and electrodynamic fundamentals of space tethers and the unique capabilities they afford (that are enabling to certain types of space missions); to elucidate the nature, cause, and solution of the early developmental problems; and to provide an update on progress made in development of the technology. Finally, it is shown that (1) all problems experienced during early development of the technology now have solutions; and (2) the technology has been matured by advances made in strength and robustness of tether materials, high voltage engineering in the space environment, tether health and status monitoring, and the elimination of the broken tether hazard. In view of this, it is inexplicable why this flight-validated technology has not been utilized in the past decade, considering the powerful and unique capabilities that space tethers can afford that are, not only required to carryout, otherwise, unobtainable missions, but can also greatly reduce the cost of certain on-going space operations.
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### Developmental History of Space Tethers

<table>
<thead>
<tr>
<th>Timeline</th>
<th>Description</th>
<th>Projects/Equipments</th>
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<tbody>
<tr>
<td>1970's</td>
<td>Dynamics of long gravity-gradient stabilized tethers shown feasible</td>
<td>Giuseppe Colombo &amp; Mario Grossi, SAO</td>
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<tr>
<td>1979-80</td>
<td>NASA/OSSA Facilities Requirements Definition Team (FRDT)</td>
<td>Peter Banks, chair (U of Mich.)</td>
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<tr>
<td>1980's</td>
<td>Technological interests formulated</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- electrical power generation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- orbital transfer</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- de-orbit, etc.</td>
<td></td>
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<tr>
<td>August 1992</td>
<td>TSS-1</td>
<td>Electrodynam: 20-km conducting tether</td>
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<tr>
<td></td>
<td></td>
<td>w/Reel-type deployer (NASA/ASI)</td>
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<tr>
<td>1993, 1994</td>
<td>SEDS-1 and 2</td>
<td>Dynamic: 20-km Non-Conducting Tether</td>
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<tr>
<td></td>
<td></td>
<td>w/ Spindle Type Deployer (NASA)</td>
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<tr>
<td>June 1993</td>
<td>PMG</td>
<td>Bi-polar operation; i.e., generator and</td>
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<tr>
<td></td>
<td></td>
<td>motor modes (NASA)</td>
</tr>
<tr>
<td>February 1996</td>
<td>TSS-1R</td>
<td>Electrodynam: 20-km conducting tether</td>
</tr>
<tr>
<td></td>
<td></td>
<td>w/Reel-type deployer (NASA/ASI)</td>
</tr>
<tr>
<td>June 1996</td>
<td>TiPS</td>
<td>Dynamic: 4 km long x 2 mm diameter tether</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(NRL)</td>
</tr>
</tbody>
</table>
As altitude increases
L, E (total energy, T (period) increase
V, F_g, F_c decrease
Tethered Satellite Orbital Dynamics

\[ F_g + T = F_c \]

\[ F_g = F_c + T \]

\[ F_g \neq F_c \]
Generation Mode

Motor Mode

\[ F = i (L \times B) \]

i up ➔ Negative Acceleration

i Down ➔ Positive Acceleration
\[ \sum M_1 = (L/2)F_T \cos \alpha - LF_2 \sin \alpha = 0 \]
\[ F_T = \int_0^L \text{d}f_{ed} = I B \cos \alpha (L) \]
\[ X_c = \left( \int_0^L r \text{d}f_{ed} \right)/F_T = L/2 \]
\[ F_2 = m_2 \left[ \left( V_1^2 / r_2 \right) - \left( MG/r_2^2 \right) \right] \]
\[ M_2 = \frac{(F_T \cos \alpha)/2}{2 \left[ \left( V_1^2 / r_2 \right) - \left( MG/r_2^2 \right) \right]} \]
Positive Results from Tether Missions

Dynamics
- **Dynamic Stability (TSS-1)**
  Gravity-gradient stabilization achieved at < 300 m.
- **Ease of Deployment and Control (SEDS-1/2 & TSS-1)**
  Deployment to 20 km, station keeping for more than 20 hrs, and satellite retrieval have been demonstrated.
- **Recovery from Dynamic Upsets & Slack Tether**
  TSS recovered from severer dynamic perturbations, slack tether and satellite pendulous motions.
- **Retrieval (TSS-1)**
  Near retrieval (most critical aspect) from 276 m was nominal (shown at right).

Electrodynamics
- **Current collection in space ten times more efficient than predicted (TSS-1R)**
  Even greater efficiency obtained w/gas emissions. Pre-TSS theoretical models much too conservative.
- **Energy conversion from spacecraft orbit into electrical power demonstrated (TSS-1R)**
  A peak power of > 3.5 kW was generated.
- **Bi-polar operations (PMG)**
  Polarity and current flow reversal performed, demonstrating power and propulsive thrust generation.

Hardware Flight Heritage
- **Tether Survivability Demonstrated In-Space (TiPS)**
  The TiPS tether (2 mm x 4 km) remains intact on orbit for 10 years.
- **Deployer In-Space Validation (6 missions)**
  Successful deployment with simple spool deployer (SEDS-1 & 2, PMG and TiPS), and with real type (TSS).
TSS Data –vs– Standard Theory

Graph showing the relationship between satellite voltage (Volts) and the ratio $I/I_0$. The graph includes a line labeled 'Parker-Murphy'.
Usable Power: TSS-1R Data vs Theory

Maximum Available Power

\[ P = I(\Phi_s - \Phi_0) \text{ Watts} \]

Tether Current (Amps)
Open Issues

- **Tether long-term survivability** in meteorite, debris, and atomic oxygen environments
- **Broken Tether Hazard**
  entanglement of mother s/c by slack tether following rebound
- **Stability**
  long-term electrodynamic-dynamic coupling (with tether current)
- **Deployer development**
  simple, robust, low mass, multi-purpose
- **Plasma contactor development**
  simple, low consumables, mass and power—or passive
Grid-Sphere Low-Drag Electrode

\[ \nabla^2 \phi = \rho(r) \]
SOLEX

Plasma Mode Discharge

SOLEX-2C
Expellant-Sustained
1.8-A Discharge
Long-Life Tether Designs

Primary Lines
Secondary Lines (initially unstressed)
0.2 to 10's of meters
0.1-1 meter

First Level of Secondary Lines Redistributes Load to Adjacent Nodes
Severed Primary Line

Effects of Damage Localized
Second Level of Secondary Lines Redistributes Load Back to Undamaged Portion of Primary Line

Prototype Hoytether Tether
Tether Optical Fiber Impact Monitor

Solar-Powered End-Body

Tether With Optical Impact Monitor

Rebound

$V_R$

Rebound (-)

Guillotine

$V_R$

Rebound (+)

International Space Station

Tether With Multiple Optical Fibers Woven Into Outer Sheath

Reflector

Single Fiber

Emitter

Detector

Control and Timing

Tension Zeros At Orbi ter

Speed ($V_R$) ~3 km/sec

Tension Zeros At End Body

GMT(sec) 29:45 29:15 29:20 29:25 29:30

Lat(deg) 1 2 2 2 2

Lon(deg) -98 -100 -100 -100 -99

TSS-1R Tether Break Relaxation

Tether with Optical Fiber Impact Monitor
Dynamic Up-Set and Relaxation

Magnetic Field

Deployed Tether Length

1992/218/01:40:00:296

100 140 180 220 260

1:45 1:50 1:55 2:00 2:05 2:10 2:15 2:20 2:25

GMT(min)
TSS-1R Tether-Break

Diagram:

- Circuit with labeled voltage (3500 V) and current (0 A).
- Circuit with labeled voltage (1000 V) and current (1 A).
- Circuit with labeled voltage (100 V) and current (0 A).
- Circuit with labeled voltage (600 V) and current (0 A).
- Circuit with labeled voltage (3500 V) and current (0 A).
TSS Tether Construction

<table>
<thead>
<tr>
<th>Property</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>2.54 mm (0.1 in)</td>
</tr>
<tr>
<td>Max Mass</td>
<td>8.2 kg/km (5.5 lb/kft)</td>
</tr>
<tr>
<td>Breakstrength</td>
<td>1780 N (400 lb)</td>
</tr>
<tr>
<td>Temp Range</td>
<td>-100° to +125° C (-148° to +257° F)</td>
</tr>
<tr>
<td>Elect Characteristics</td>
<td>Carry 1-A Current at 10 kV</td>
</tr>
<tr>
<td></td>
<td>0.2 Ω/m</td>
</tr>
<tr>
<td></td>
<td>5 mA (Max) Leakage</td>
</tr>
<tr>
<td>Max Elongation</td>
<td>5% at 1780 N</td>
</tr>
</tbody>
</table>
Classical ED Configuration

\[ F = I \ (B \times L) \]

\[ I = J A_{\text{sheath}} \]
\[ = e \ n_o A \ (kT_e/m_e)^{1/2} \]
\[ \frac{4}{4} \]
Orbital ED Force Variations

**Tether**
- Type: Insulated
- Length: 2.5 km

**Electrode**
- Diameter—15 m dia
- Grid-Sphere
- Bias— +50 V

**Orbit**
- Altitude—400 km
- Inclination—51.5°

**Current Collection**
Model—Parker-Murphy EBC

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**Resulting Force Variation**

![Graph showing force variation over time]

- Average Force
- 0.06 of Peak Current

**Diurnal Density Variation**

![Graph showing density variation over time]
Magnetospheric Plasma Profile

Synchronous Orbit (42,100 km)

Region of Classical Electrodynamic Tether Operations
“Vacuum-Field” Configuration

\[ F = I (B \times L) \]

Electron Emission

Magnetic Field \( B \)

Very Low Plasma Density

Ion Emission

\( V_0 \)
ElectroDynamic Propulsion

Unique Capabilities

- Orbit Control
- Drag ΔV Recovery
- Electrical Power Generation
- LEO-GEO Operational Range (170-42,000 km)
- Long-Life Capability (10+ yrs)

EDP uses no propellant—it taps directly into the Earth’s rotational energy by coupling to the geomagnetic field via a solar powered current system.
Comparative "Propellant" Efficiencies

Electrodynamic*
~100,000 s to
~1,000,000 s

* Increases with Tether Length

\[ F = I (B \times L) \]
Characteristics & Capabilities

- Device Masses < 2% of host mass
- Dormant during satellite operation
- Deploys tether when satellite dies
- Tether drags against geomagnetic field, de-orbits satellite in weeks
- No propellant required
- Self-powered — needs no input power
- Can deorbit a dead satellite
Hubble Boost Using Electrodynamic Propulsion

Micro-sat End-Body

\[ F = (I \times B)L \]

Contactor Plume

\( V_0 \)
Rational for ED Boost of HST

Raising HST to a Permanent Parking Orbit:

- Removes HST from active space w/o its destruction and at potentially a lower cost to NASA.
- Circumvents any possibility of impacting populated regions on earth.
- Provides flexibility—allows extended orbit maintenance and future recovery from parking orbit.
ISS Tether Reboost System (TRS)

TRS Design Features

- Twin 2.5 km electrodynamically conductive tethers
- Enables orbit maintenance and reboost
- Only mechanical interface with ISS
- Uses no Station power
- Acceptable Station CM shift (<3 m)
- Naturally stabilizes station attitude (roll axis)
- No expellant re-supply over design life (5 yr)
- Total system mass <1000 kg
- Tether monitoring & break protection
- Instantaneously jettisonable
The Momentum-eXchange/ Electrodynamic Reboost (MXER) Tether Facility is a reusable, propellantless, in-space upper stage for sending payloads from LEO to GTO and beyond.

- Tether is 90-120 km long and operates in an elliptical, equatorial orbit.
- Rapid rotation of the tether allows its tip to match position and velocity with the payload instantaneously.
- Orbital energy given by the tether to the payload is restored over 30-45 days using electrodynamic tether propulsion.
Jovian Electrodynamic Capture

Tether Applications
- Deboost for Capture
- Orbit Adjustment
- Electric Power

Hyperbolic Intercept

Electrodynamic Decay Region
($\Delta V$ in km/sec)

0.03
0.06
0.12
0.33
0.73

Perijove = 1.2 $R_J$
($R_J = 71,900$ km)

Parabolic 100 Day Capture Orbit

$V_\infty = 5$ km/sec

Tether System
- Spacecraft Payload Mass 500kg
- 10km Conducting Tether
- Tether Resistance: $96\Omega$
- Plasma emitter at each end
- Propulsion Mass Budget
  - Tether 98kg
  - Emitter Expellant 22kg
  - Deployer and Controls $\leq 128$kg
  - Total $\leq 240$kg

(0.5 km/sec $\Delta V$ required for capture)