SPACE TETHERS

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Abstract

Tethers have been studied and validated in space since the 1960’s, and many studies show their applicability across a broad range of applications, including space propulsion, power generation, formation flying, multi-point ionospheric science, and active space debris removal. Important milestones include retrieval of a tether in space (Tethered Satellite System 1992), successful deployment of a >30-km tether in space (Young Engineer’s Satellite 2, 2007), operation of an electrodynamic tether with tether current driven in both directions—power and thrust modes (Plasma Motor Generator 1993), high tether current capability (Tethered Satellite System Reflight 1996), demonstration of a long-term (~10 year) tether operation on-orbit (Tether Physics and Survivability Experiment 1996 – 2006), and the successful deployment of a tape tether (Japan Tether Experiment 2010). Various types of tethers and systems could be used for space applications. Electrodynamic tethers can use solar power to ‘push’ against a planetary magnetic field to achieve propulsion without the expenditure of propellant.Utilizing completely different physical principles, long non-conducting tethers can exchange momentum between two masses in orbit to place one body into a higher orbit or a transfer orbit for lunar and planetary missions. Tethers can also be used to support space science by providing a mechanism for precision formation flying, fixed-
baseline multi-point science observations, and for reaching regions of the upper atmosphere that were previously inaccessible.

1. Introduction

Since the 1960’s, there have been at least 19 tether missions. In the last two decades, several important milestones were reached, including:

1) Retrieval of a tether in space - Tethered Satellite System (TSS-1, 1992) (Ref. 1)
2) Successful deployment of a 20-km-long tether in space - Small Expendable Deployer System (SEDS-1, 1993 and SEDS-2, 1994) (Ref. 2)
3) Operation of an electrodynamic tether with tether current driven in both directions; power and thrust modes - Plasma Motor Generator (PMG, 1993) (Ref. 3)
4) Generation of high power (3 kW on TSS-1 Reflight, 1996) (Ref. 4)
5) Demonstration of a long-term (~10 year) tether operation on-orbit - Tether Physics and Survivability Experiment (TiPS, 1996-2006) (Ref. 5)
6) Successful deployment of the longest (>30-km) tether in space (Young Engineer’s Satellite 2, 2007) (Ref. 6)
7) Successful deployment of the world’s first electrodynamic tape tether (Japan Tether Experiment, T-Rex, 2010)(Ref. 7)

Table 1 shows a list of known tether missions.

Table I. Prior tether flight mission results. Note: Most have been completely successful.

<table>
<thead>
<tr>
<th>Year</th>
<th>Mission</th>
<th>Type</th>
<th>Description</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1966</td>
<td>Gemini-11</td>
<td>Dynamics</td>
<td>• 15-m tether between capsules&lt;br&gt;Tethered capsules set in rotation</td>
<td>+ Successful deployment and stable rotation</td>
</tr>
<tr>
<td>1966</td>
<td>Gemini-12</td>
<td>Dynamics</td>
<td>• 30-m tether between capsules&lt;br&gt;Tethered capsules set in rotation</td>
<td>+ Successful deployment and stable rotation</td>
</tr>
<tr>
<td>1989</td>
<td>OEDIPUS-A</td>
<td>ED/Plasma Physics</td>
<td>• Sounding rocket experiment&lt;br&gt;958-m conducting tether, spinning</td>
<td>+ Successful EM coupling between conducting tether ends through tether-guided wave modes&lt;br&gt;+ Obtained data on behavior of tethered system as large double electrostatic probe</td>
</tr>
<tr>
<td>Year</td>
<td>Experiment</td>
<td>Discipline</td>
<td>Description</td>
<td>Outcomes</td>
</tr>
<tr>
<td>------</td>
<td>------------</td>
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</tr>
<tr>
<td>1992</td>
<td>TSS-1</td>
<td>ED/Plasma Physics</td>
<td>20-km insulated conducting tether to study plasma-electrodynamic processes and tether orbital dynamics</td>
<td>Tether deployment stopped after only 0.260 km; deployer jammed due to the too-long bolt + Demonstrated stable dynamics of short tethered system + Controlled retrieval of tether</td>
</tr>
<tr>
<td>1993</td>
<td>SEDS-1</td>
<td>Momentum Exchange</td>
<td>Deployed payload on 20-km nonconducting tether and released it into suborbital trajectory</td>
<td>Successful, stable deployment of tether + Demonstrated deorbit of payload</td>
</tr>
<tr>
<td>1993</td>
<td>PMG</td>
<td>ED</td>
<td>500-m insulated conducting tether + Hollow cathode contactors at both ends</td>
<td>Demonstrated ED boost and generator mode operation</td>
</tr>
<tr>
<td>1994</td>
<td>SEDS-2</td>
<td>Dynamics</td>
<td>Deployed 20-km tether to study dynamics and survivability</td>
<td>Successful, controlled deployment of tether with minimal swing – Tether severed after 3 days in space</td>
</tr>
<tr>
<td>1995</td>
<td>OEDIPUS-C</td>
<td>ED/Plasma Physics</td>
<td>Sounding rocket experiment + 1174-m conducting tether, spinning</td>
<td>Obtained data on plane and sheath waves in ionospheric plasma</td>
</tr>
<tr>
<td>1996</td>
<td>TSS-1R</td>
<td>ED/Plasma Physics</td>
<td>20-km insulated conducting tether to study plasma-electrodynamic processes and tether orbital dynamics</td>
<td>Electrodynamict performance exceeded existing theories + Demonstrated ampere-level current – Flaw in insulation allowed high-voltage arc to cut tether prior to full deployment</td>
</tr>
<tr>
<td>1996</td>
<td>TiPS</td>
<td>Dynamics</td>
<td>Deployed 4-km nonconducting tether to study dynamics and survivability</td>
<td>Successful deployment + Tether survived over 10 years on orbit</td>
</tr>
<tr>
<td>1999</td>
<td>ATEx</td>
<td>Dynamics</td>
<td>Tape tether deployed with pinch rollers</td>
<td>Deployment method “pushing on a rope” resulted in unexpected dynamics – Deployed only 22 meters before experiment was terminated</td>
</tr>
</tbody>
</table>
Space transportation can also utilize various types of tethers and systems. Long non-conducting tethers can exchange momentum between two masses in orbit providing an effective orbit transfer or de-orbit capability. Electrodynamic tethers can use solar power to ‘push’ against a planetary magnetic field to achieve propulsion without the expenditure of propellant. Tethers can also be used to support space science by providing a mechanism for precision formation flying, fixed-baseline multi-point science observations, and for maintaining orbits in regions of the upper atmosphere that would require continuous expenditures of propellant due to drag effects.

Below are descriptions of the main types of tether systems.

2. Electrodynamic Tether Propulsion

A long conducting tether, terminated at each end by a plasma contactor, can be used as an electrodynamic tether (EDT) thruster seen in Fig 1. EDT thrusters work by virtue of the force a magnetic field exerts on a wire carrying an electrical current. The force acts in a direction perpendicular to both the direction of current flow ($I$) and the magnetic field vector ($B$) ($F = I L \times B$, where $L$ is the length of the tether). An EDT thruster is just a clever way of getting an electrical current to flow in a long orbiting wire (the tether) so that the Earth’s
magnetic field will accelerate the wire and, consequently the payload attached to the wire. The direction of current flow in the tether, either toward or away from the Earth along the local vertical, determines whether the magnetic force will raise or lower the orbit. The tethered system extracts electrons from the ionospheric plasma at one end (upper or lower, depending upon the deployment direction and intended thrust motion) and then carries them through the tether to the other end, where they are returned to the plasma. The circuit is completed by currents in the plasma. This concept will work near any planet with a magnetosphere – which includes the Earth and Jupiter (Ref. 8). Although the propulsive force effect was not directly measured, the TSS-1R mission demonstrated this ability to drive significant current (~ 1 A); during the mission, the orbiter experienced a 0.4-N electrodynamic drag thrust during tether operations (Ref. 9).

Figure 1. Electrodynamic tethers use the Lorentz force to create thrust.

Thus, an electrodynamic tether upper stage could be used as an orbital tug to move payloads within low-Earth orbit (LEO) after insertion. The tug would rendezvous with the payload and launch vehicle, dock/grapple the payload, and maneuver it to a new orbital altitude or inclination within LEO, without the use of boost propellant. The tug could then lower its orbit to rendezvous with the next payload and repeat the process. Such a system could conceivably perform several orbital maneuvering assignments without resupply; making it a low-recurring-cost space asset.

The tether performance peaks between about 300 and 400 km for all orbital inclinations. Below 300 km, atmospheric drag on the tether begins to dominate the thrust, decreasing the overall performance of the system. As the operational altitude increases above 400 km, the
Earth’s plasma density gradually decreases, making less current available for tether thrust, while useful thrust is possible above 1,000 km altitude. Peak tether thrust is obtained when the component of the propulsive force \((F = IL \times B)\) along the flight direction is maximized, which occurs at low orbital inclinations.

This same system can be used to change the orbital inclination of a payload as well. The performance of electrodynamic tethers for changing orbital inclination varies with altitude and starting inclination. Peak performance for this application is obtained when the component of the propulsive force orthogonal to the orbital plane is maximized, which occurs at high orbital inclinations. Tether performance again decreases with altitude due to the decreasing plasma density.

Specific potential electrodynamic tether propulsion applications are described below:

**Orbital Tug for Orbital Debris Removal and Supporting Orbital Propellant Depots**

NASA/JSC studies indicate preventing runaway growth of the orbital debris population requires removal of 5-10 large objects per year (Ref. 10). Deploying a single system, to remove many debris objects, requires a very large total \(\Delta V\) capability in order to rendezvous with multiple objects in different orbit altitudes and orbit inclinations. Near-propellantless EDT propulsion systems provide a unique capability, not only to perform many altitude change maneuvers, but also large inclination changes with a very small system mass. This can enable a single, small, affordable system to perform multiple orbital debris removal missions. An EDT-driven tug could provide sufficient thrust to enable the deorbit of a 3 ton debris object from 800 km to 300 km, releasing the object into a targeted re-entry trajectory using tethered momentum exchange, and then re-boosting itself to 800 km within a period of two months, and repeating this operation throughout a five-year mission without refueling (Ref. 11).

EDT propulsion can also enable an orbital tug to perform an extremely \(\Delta V\) intensive mission such as ferrying large (10 MT) propellant tanks from a 350 km, 28.5° drop-off orbit up to a propellant depot in a 800 km, 45° orbit, as illustrated in Figure 2A, where a tether system can perform the job with 1/10\(^{16}\) the mass of the best currently available technology.

![Figure 2](image-url)  
Figure 2. System mass comparisons electrodynamic tether propulsion versus other propulsion systems for use on an orbital tug, Bigelow station reboost, and Hubble Space Telescope deorbit missions.
LEO and Low-Altitude Station Keeping

An EDT's ability to provide relatively high thrust - for an electric propulsion (EP) system - over very long durations makes it ideally suited for providing drag-make up propulsion on space stations and other assets in low-LEO. Figure 2B shows that a tether could perform reboost of a Bigelow BA-330 commercial station over a 10-year period for dramatically less total mass than other technologies.

End of Life Deorbit

Orbital debris mitigation requirements place post-mission orbital lifetime restrictions on new spacecraft. These requirements present a significant cost and performance impediment to many missions due to the large fraction of the spacecraft mass reserved for propellant to accomplish deorbit. An electrodynamic drag tether system could lower the orbit of the debris and then use a small monopropellant insertion motor to initiate a controlled deorbit. This could reduce deorbit system mass requirements by over 75% compared to a monopropellant-only system. For example, had the Fermi Gamma-ray Space Telescope (FGST) used a tether to accomplish its deorbit requirement rather than a hydrazine thruster, it would have freed 350kg of mass for additional payloads (Ref. 12). Figure 2C shows the mass savings that could be achieved by a tether for end-of-life deorbit of the Hubble Space Telescope.

Jovian Exploration

Since the discovery of possible water oceans on Europa, there has been considerable interest in sending a mission there. Due to low solar luminosity sun, the electrical power used by Galileo and all deep space missions, prior to Juno, were radioactive thermoelectric generators (RTG). The possibility of using solar panels for electrical power generation has improved in recent years with improvements in this technology; however, the high levels of radiation in the Jovian system are expected to rapidly degrade the effectiveness of solar arrays as a result of extended exposure. Extended operations in the Jovian system, or around any planet, also typically require use of an expendable propellant for orbital maneuvering. This may lead to high “wet” spacecraft mass at launch and/or limited lifetime on orbit. It is for these reasons and because of the strong magnetic field and rapid planetary rotation that EDT's are being considered for use in the Jovian magnetosphere.

Preliminary analysis indicates that a 10-km tether can theoretically generate a megawatt of power in near Jovian space. Specifically, such a tether operating near the planet would experience induced voltages greater than 50,000 V, currents in excess of 20 A, generate approximately 1 MW of power and experience more than 50 N of thrust (Ref. 13). Unlike Earth, a tethered spacecraft in some Jovian orbits will not require an external power source, like a solar array, to produce boost thrust. In a circular equatorial Jovian orbit, due to Jupiter's rapid rotational speed, its magnetic field allows the ambient plasma to co-rotate with the planet. A spacecraft operating in this regime could use the induced Lorentz force to produce boost or deboost thrust while simultaneously generating power (Ref 14).

Of course, the engineering challenges of developing such a system are immense. For example, powers of over 1 MW can only be generated if there is sufficient tether cooling to prevent exceeding the maximum temperature limits of the tether material. In addition, managing such high voltages on a spacecraft in the Jovian space plasma environment will be difficult, to say the least. Any likely mission to Jupiter using an EDT will be much shorter and operate at much lower currents and voltages.
Multipoint Science and Sensing

By constraining two or more bodies to co-orbit, a tether can accomplish formation flight of multiple sensors without propellant. This allows multi-point ionospheric studies, long-baseline interferometry, and defense missions requiring long baselines to perform by a much smaller system than is currently possible.

EDT propulsion systems provide orbital agility to enable a single system to sample a wide range of orbital altitudes. This orbital agility also can enable a multi-mission system to change its altitude to optimize multiple sensors performance (e.g., an Earth-sensing system could repeatedly cycle between 400 km for optical measurements, 800 km for radar sensing, and 1,200 km for communications). The large EDT system ΔV capability can also enable persistence at very low altitudes of interest (<250 km) for lower thermospheric studies (Ref. 15). Figure 3 compares the system masses of EDT propelled spacecraft in formation flight to other technologies.

Orbital Power Harvesting

In ‘deboost’ mode, an EDT converts orbital energy into electrical energy that can be harvested to supply power to mission payloads. In LEO, a 10 km tether can generate >2 kW, providing a means to supply brief large power levels to payloads in eclipse without requiring large solar panels and heavy batteries. Power generated in this mode can only be provided for brief periods due to the resulting orbital altitude decay. However, this might be ideal for instruments requiring significant power when other sources are not available (for example, during eclipse). The spacecraft could then thrust and reboost when other power is available, turning the tether system into an “orbital battery.” (Ref. 16)

3. Hanging Momentum Exchange Tethers

Momentum exchange tethers provide an augmentation to launch vehicle systems, particularly reusable systems, for boosting payloads to higher orbits. This stems from the
fact the launch vehicle must reduce its altitude after payload release in order to return to Earth (for a reusable system) or to burn up after the mission is complete (for expendable systems); while at the same time the payload it ejects must increase its altitude to reach the desired orbit. In other words, momentum must be removed from the launch vehicle and added to the payload—requiring a significant fraction of propellant budget. Tethers provide a method to transfer excess momentum directly from the launch vehicle to the payload.

Operationally, this could be accomplished by deploying the payload upward on a long (~20 km) tether from the launch vehicle. The tether system is then stabilized along the local vertical by the gravity gradient force with the orbital velocity of the system determined by the altitude of its center of mass. The payload, located 20 km above the launch vehicle, is forced to orbit at a higher velocity, while the launch vehicle moves at a lower velocity. Momentum is, therefore, transferred from the relatively heavy launch vehicle directly through the tether to the payload. When the tether separates, the center of mass orbit remains the same; while the satellite injects into a higher orbit with apogee increased about seven times the tether length (140 km for this case) and perigee at the release location and the launch vehicle drops into a lower orbit with apogee at the release location.

When the electrodynamic tether broke on the TSS-1R flight, sending the end mass into a new, higher orbit, this inadvertently demonstrated momentum exchange. The technology for this type of momentum exchange utilizing a tether exists today and was successfully demonstrated with the SEDS in 1993 and the YES 2 in 2007.

4. Rotating Momentum eXchange Electrodynamic Reboost (MXER) Tethers

In the long-term, a spinning tether system can be used to boost payloads into higher orbits with a Hohmann-type transfer (Ref. 17). A tether system would be anchored to a relatively large mass in LEO, awaiting rendezvous with a payload delivered to orbit. The uplifted payload meets with the tether facility which then begins a slow spin-up using electrodynamic tethers (for propellantless operation) or another low-thrust, high-specific impulse thruster. At the proper moment and tether system orientation, the payload is released into a transfer orbit—potentially to geostationary transfer orbit (GTO) or lunar transfer orbit (LTO). A network of such systems could be developed to “hand off” a payload until it reaches the desired location.

The physics governing a rotating momentum exchange system is illustrated in Figure 4. Following spin-up of the tether and satellite system, the payload is released at the local vertical. The satellite injects into a higher orbit with perigee at the release location; the orbital tether platform is injected into a lower orbit with apogee at the release location. The satellite enters a GTO trajectory and accomplishes the transfer in as little as 5-16 hr, where the lower number applies to a single-stage system and the higher number to a two-stage system. The orbital tether platform then undergoes reboost to reclaim the momentum transferred to the payload and reacquire its operational altitude. Reboost is accomplished by electrodynamic propulsion or using electric thrusters. Transfer times are comparable to a chemical upper stage with the efficiencies of electric propulsion.
Figure 4. The orbits of a launch vehicle and satellite after release from a rotating momentum exchange tether system.

The orbital tether platform therefore becomes a reusable “in-space upper stage” for payload and spacecraft transport from LEO to GEO and deep space trajectories (Ref. 18).

It should be emphasized that the scenario described above is highly speculative with many outstanding technical and cost issues to be resolved before it can be seriously considered for implementation. Technical issues include the development of long-life, survivable conducting and nonconducting tethers, deployers, no-expellant anodes and cathodes, advanced rendezvous techniques, and a robust tether dynamics modeling capability. A detailed analysis is needed to determine the amortized cost for a reusable boost station (how many boosts can the system perform before is replaced? What does it cost to develop, build and launch each station?) so that a fair pricing structure can be determined and allow its true per-mission costs to be determined.

Nonetheless, by offloading a large fraction of the mission $\Delta V$ from the launch vehicle to a reusable in-space upper stage, these systems could significantly reduce launch costs for GEO and deep space missions by enabling these missions to be launched on smaller, less expensive rockets as shown in Fig 5.
Figure 5. Tether in-space upper stages enable exploration missions to reduce launch costs. The quoted IMLEO masses do not include the mass of the reusable MXER tether boost station; all mission concepts cited currently plan to use Solar Electric Propulsion (SEP).

5. Conclusions

The world’s space agencies and commercial companies are considering space tethers for a broad range of applications, including space propulsion for orbital tugs and debris removal, formation flying, multi-point ionospheric science, and as reusable space-based boost systems. One of the most promising applications for tethers is in the area of space propulsion and transportation. Momentum exchange tethers offer payoff a high-risk/high-payoff approach for transfer of payloads between LEO and GEO, GTO and lunar space. In addition, the many benefits of their use in support of space science have been recognized for many years. Tether technology has advanced significantly since its inception over 40 years ago and is ready to move from experiment and demonstration to application.

6. References


