# Applications of Tethered Space Systems in Spacecraft Propulsion

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# 1 Introduction

The goal of this project was to investigate the use of tethered space systems within space missions as part of the propulsion and attitude control of satellite systems. Tethers in space have a variety of applications, ranging from orbit maneuvers and propulsion to attitude stability. Tethers can also be used in space applications to maintain contact between two satellites or space vehicles, such as a rendezvous between the International Space Station (ISS) and the Space Shuttle. These space tethers can be conductive or non-conductive, depending on the application, and are usually long, thin, strong cables or wires running between the two components of the space system. This paper will first give an overview of tethered systems. It will then continue by introducing the main distinctive types of tethers with approaches and modern techniques of implementing tethered systems today. Next, this paper will delve into an analysis of the propulsive capabilities of tethered space systems, including practical applications for the basic tethered systems. This will be followed with a discussion of space missions that have incorporated tethered systems, their importance and implementation into the mission, and the success of the system in the mission. Finally, this paper will close with a look at conceptual and future ideas for the application of space tethered systems.

# 2 Overview of Tethered Systems

A tethered space system is one in which two bodies are connected via a long cable. This long cable can be used to couple spacecraft to each other or to another mass, such as a space station or an asteroid. Space tethers are typically made of thin strands of high-strength fibers or conducting wires. These tethers need to be made of materials with high strength and low density in order to withstand the tensile loads of the systems. They must also be protected against micrometeoroids and the harsh space environment. These tethers can be conductive in nature, exhibiting electromagnetic characteristics by converting electric energy to potential energy and visa versa. An example of a tethered space system is shown below in Figure 1.

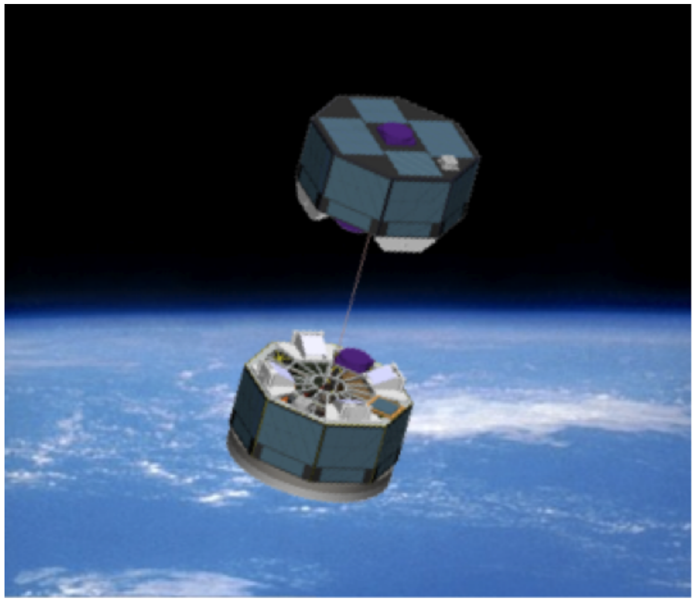

Figure 1: Tethered SATellite Testbed (TSATT) Concept Drawing [1]

Tethered systems provide propellantless propulsion that can be used in attitude control, orbit transfers, momentum dumping, station-keeping, and a variety of other applications. A mechanical connection is established through the tether that enables the transfer of energy and momentum from one object to the other. This system provides propulsion to one body without the use of propellant, which can be heavy and costly to transport into space. Other ways that space tethers generate energy for thrust (or negative energy for drag) is through the interaction between a conductive space tether and the ionospheric plasma in Earth's magnetic field [2]. This method creates electric potential across the tether that can be converted to kinetic energy for the spacecraft.

Tethers in space can also provide a physical connection between two bodies in order to maintain formation flying. For missions requiring precision measurements from multiple satellites in close proximity or with repeated rendezvous and docking, space tethers provide a system through which these processes can take place. Space tethers also provide the means for information to flow freely between the components of the system. Docking between the Space Shuttle and the ISS is very important and allows for the transport of cargo and astronauts back and forth; this docking is done through the use of a space tether system. This physical connection between the shuttle and the space station allows the two spacecraft to maintain an orbit together while the shuttle is docked. Figure 2 below displays this deployable docking mechanism.

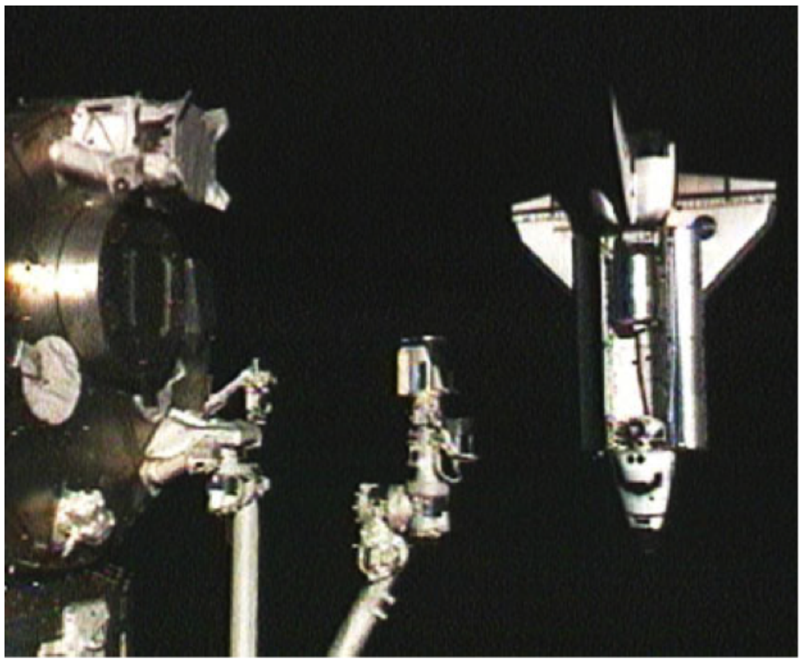

Figure 2: Space Shuttle Endeavour Docking with the Space Station [3]

The tethers used in space applications are unique due to the fact that they must have a deployable mechanism. Spacecraft are transported aboard launch vehicles where size and mass are limited. During launch, the spacecraft are exposed to high stresses, vibrations, and other loads that could be detrimental to an exposed tether due to its long, thin nature. Therefore, the tether must be deployed in space where the absence of gravitational forces make it possible to extend the tether without compromising its structure. For a more in-depth analysis of the dynamics of deploying and retracting space tethers, I recommend Dr. Eugene Levins book, noted in the references section of this paper.

# 3 Types of Tethered Systems

While the overall family of tethered systems can be used on a variety of mission types, this paper will highlight a few of the more common space tether systems in use today. The first type of tether system that will be examined is the momentum exchange tether system. In this system, one spacecraft gains momentum and another loses momentum. This transfer of momentum is performed through the interactions in joining the two with a tethered connection, followed by the severance of this connection. One spacecraft effectively generates the propulsion of another in order to perform orbit maneuvers or station-keeping.

Within the distinction of momentum exchange systems, there are different ways for tethers to perform this maneuver. One method for gaining momentum is to use a capture-toss process, outlined in Figure 3. Effectively, one spacecraft will rendezvous with another object, capture the object with a mechanical tether system called a bolo, and then toss the object into an orbit trajectory with a higher energy while reducing its own orbital energy.

As you can see in the top left picture of the figure, the yellow spacecraft will be performing the capture of the blue spacecraft. The initial orbital velocities of yellow spacecraft ($V_{yi}$) and the blue spacecraft ($V_{bi}$) are given by:

$$V_{yi} = \sqrt{\frac{\mu}{R_{1i}}} \tag{1}$$

$$V_{bi} = \sqrt{\frac{\mu}{R_{2i}}} \tag{2}$$

As the maneuver progresses, the spinning mechanical tether allows the two spacecraft to combine as one system and travel on a trajectory together (top right photo).

$$V_{System} = \sqrt{\frac{\mu}{R_{2i} + L}} \tag{3}$$

In Equation 3, $L$ is the length of the tether separating the two spacecraft.

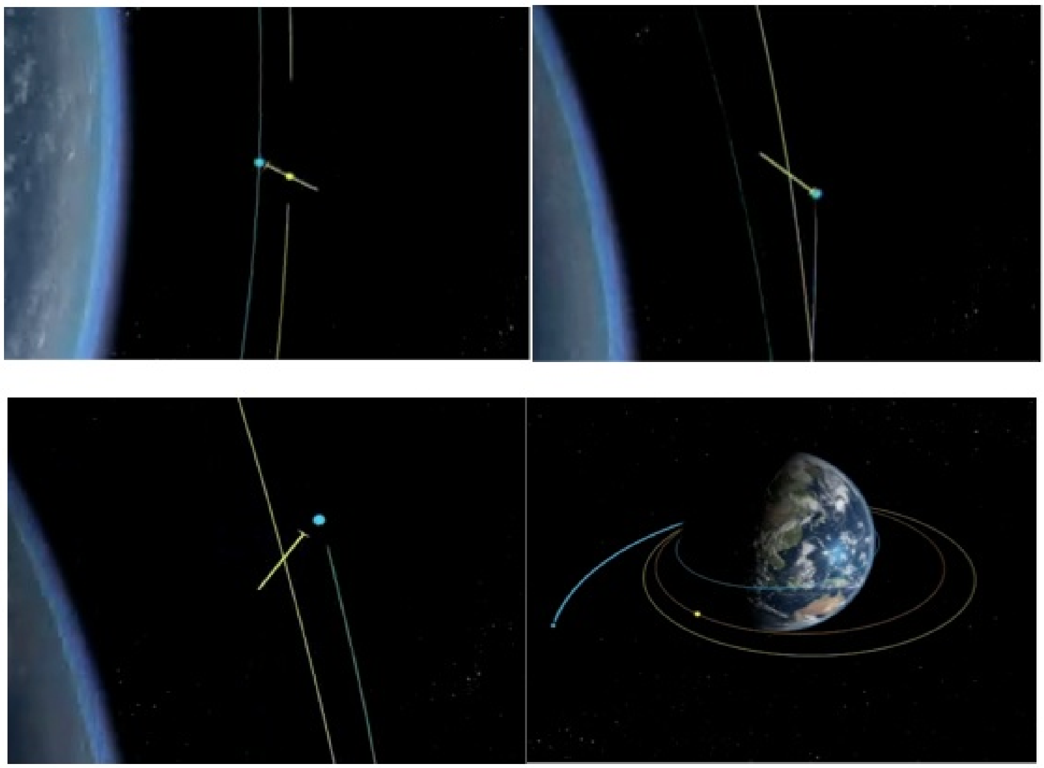

Figure 3: Momentum Exchange Tether System Capturing and Tossing a Payload into a Higher Altitude Orbit [2]

Moving down to the next picture in the bottom left of the figure, the momentum exchange that occurs from the yellow spacecraft to the blue one happens through the severance of the tether. The location of this event is critical in determining the velocity vectors of both spacecraft and their new orbital trajectories, given by Equations 4 and 5 below.

$$V_{yf} = \sqrt{\frac{\mu}{R_{1f}}} \tag{4}$$

$$V_{bf} = \sqrt{\frac{\mu}{R_{2f}}} \tag{5}$$

In examining the final velocities, $V_{yf} < V_{yi}$ and $V_{bf} > V_{bi}$ . As can be seen in the final picture, the yellow spacecraft, now on the red orbit path, is located at a lower altitude in a lower energy orbit while the blue spacecraft that has gained energy is on a much higher energy orbit than its previous light blue trajectory close to the planet. For this blue spacecraft, the point of the orbit that was its apogee is now its perigee. When the spacecraft reaches its new apogee, it has the potential to fire an engine to circularize its orbit. Through exchanges such as this, spacecraft are able to perform orbit maneuvers to boost payloads from LEO to GEO, allow for payloads to transfer momentum from a comet or asteroid to obtain a new orbit trajectory, and perform escape maneuvers from gravity fields.

This same principle of momentum transfer is executed using the gravity gradient around a planet or other body of mass in space (i.e. moon, comet, asteroid, etc.). To use the gravity gradient force, the two tethered bodies must be separated by sufficient distance to where the gravitational force (shown below in Equation 6) is substantially different.

$$F = \frac{GmM}{r^2} \tag{6}$$

As you can see from the equation for gravitational force, when the distance between the objects increases, the force decreases. Therefore, an object orbiting at a larger radius experiences the interaction of a smaller force, which thereby provides less momentum and a slower velocity. This system is shown below in Figure 4.

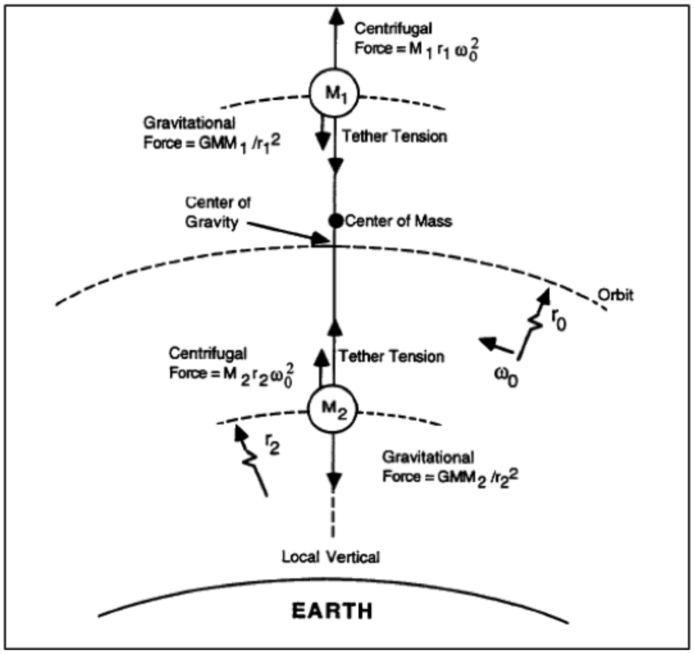


Figure 4: Tethered System in a Gravity Gradient Field [4]

When a mechanical tether connects the two objects, they must move as a system about their center of mass. This provides an increase in the momentum of the object in higher orbit altitude and a decrease in the momentum of the object in the lower orbit altitude. Effectively, the upper mass orbits at a velocity that is faster than its orbit allows and the lower mass is too slow for its orbit. The total momentum of the system, however, is conserved. When the two have exchanged momentum, the tether connection can be severed and the two spacecraft will travel on new orbital paths [5].

Another type of tether is an electrodynamic tether system. An electrodynamic tether is composed of a conducting wire that interacts with the Earths magnetic field to create electric potential that can then be converted to kinetic energy for the spacecraft. As the tether moves through the magnetospheric plasma, electrons accumulate on one side, creating an electric potential and generating a current. This current produces a directional Lorentz-force ($F = I$ x $B$) that the spacecraft can use to increase or decrease its kinetic energy and perform the necessary orbital maneuver [5]. The principle of electrodynamic propulsion with a space tether is outlined in Figure 5.

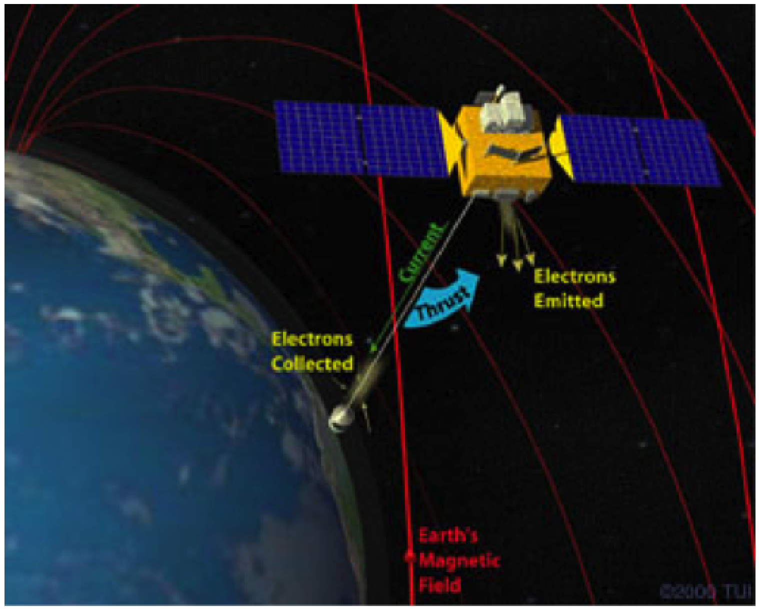


Figure 5: Electrodynamic Propulsion Provided by a Tether System [2]

Electrodynamic tether systems can be used in station-keeping to perform orbit re-boost, an orbital thrust maneuver that boosts a spacecraft back its original orbit. This re-boost process counteracts the orbit degradation, resulting from such forces as atmospheric drag in the gravity-field, solar radiation pressure, or other perturbations. Electrodynamic tethers generate energy from their surrounding space environment, eliminating the need to carry propellant, an item that is costly, weighty, and ultimately exacerbates its supply.

The implications of employing an electrodynamic space tether on board spacecraft have been gaining popularity over the past two decades [6]. In addition to station-keeping and attitude stabilization, electrodynamic tethers can be deployed as a passive solution for end-of-life maneuvers and satellite de-orbits. According to Dr. Eugene Levin, tether systems would have been very helpful to both Mir and the International Space Station as a cheap and effective way maintain their orbits and to extend their lifetimes [6].

A unique approach to providing in-space propulsion to multiple spacecraft combines both the momentum exchange and the electrodynamic re-boost tether systems. In order to perform consecutive maneuvers, this system itself must replace the energy it loses in the momentum exchange. By coupling the momentum exchange tether with an electrodynamic tether system, the system can capture-toss a spacecraft into a higher energy orbit and then slowly re-boost itself back to its original orbit to repeat the process.

# 4 Analysis of the Propulsive Capabilities and Applications of Tethered Systems

In all space missions, mass is arguably the biggest constraint. For each kilogram of payload mass, propellant is needed not only for the launch into space, but also for any orbital maneuvers and station-keeping throughout the lifetime of the mission. Currently, the average cost to launch a kilogram of payload mass into Low-Earth Orbit (LEO) is $10,000 [7]. Therefore, a tethered system that does not require propulsion to transfer momentum to spacecraft or provide station-keeping is an attractive alternative that promises to cut mass and ultimately cost of future space missions.

According to the Electrodynamic Tether Re-boost Study performed for the International Space Station, electrodynamic tethers (EDTs) can provide the re-boost necessary for the station to maintain its orbit in the presence of atmospheric drag [8]. At present, firing thrusters on board the Russian Progress vehicle is the primary method used to boost the ISS to a higher orbit, although other vehicles such as the European Space Agencys ATV have this capability as well. Over the past five years, an average of 10,000kg of propellant was needed annually to re-boost the station [8]. This amount of propellant equates to 6 resupply missions over the course of a year, at a cost of roughly $35 million each [7]. With the proposed EDT system, two of these resupply missions could be eliminated each year, saving $70 million [8]. With the stations proposed end-of-life in 2020, half a billion dollars could be saved by equipping the ISS with an EDT.

The proposed EDT system for the ISS would use a relatively short and light tether (10km long and 200kg) to generate an average of 0.5-0.8N of thrust [8]. For comparison, the atmospheric drag that the station experiences ranges from 0.3-1.1N, depending on the year and the atmospheric fluctuations [8]. The EDT will require 5-10kW of power to generate this range of thrust, calculated from Equation 7 below [9].

$$P(kW) = \frac{1}{1000}(\frac{F * \nu}{\eta}) \tag{7}$$

In Equation 7, the electrodynamic tether efficiency $\eta = 0.6$ and the orbital velocity for the ISS $\nu$ is assumed to be 7.6 km/s [9].

The tether system examined in this study uses a bare-tether design that makes the electrodynamic re-boost practical with only moderate power requirements. This bare-tether design will be able to operate during the night cycles because it is relatively insensitive to the fluctuations in electron density of the ionosphere [9]. During the day cycles, the EDT system can be operated with surplus power from the solar panels, and possibly on the stations battery supply during the night cycles. A diagram of the EDT system is shown below in Figure 6.

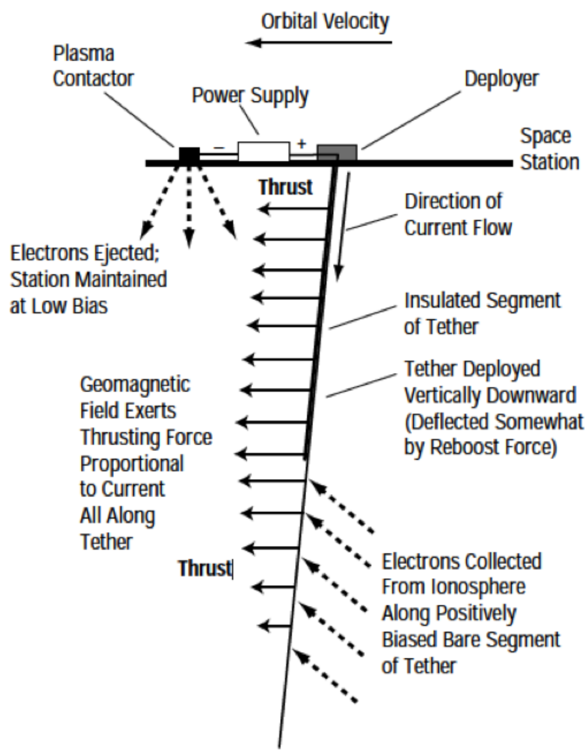


Figure 6: Electrodynamic Tether for ISS Re-Boost [8]

Challenges for a tethered re-boost system include monitoring and protecting the tether from severance by micrometeoroid impacts, installation and deployment of the tether while maintaining the stations center of mass, and power availability for the system during the day/night cycles. However, the benefits of installing this system include a low development and operational cost because the technology has a high TRL (Technology Readiness Level), increased payload capacity on resupply missions or fewer necessary resupply missions, reduced external environmental contamination from thruster exhaust, and large cost savings over the projected ISS lifetime [8]. While the station can supply its own power, it cannot supply its own propellant. Outfitting the ISS with an EDT for re-boost eliminates one of the most critical dependencies the station has on Earth  the need for propellant resupply.

While the use of EDTs for re-boosting the ISS holds potential, and in fact Tethers Unlimited Inc. (TUI) is currently developing EDTs for use on microsatellites, space tethers are plausible alternatives for performing orbital transfers. Funded by NASAs Institute for Advanced Concepts (NIAC), TUI and Boeing partnered to develop the architecture of a tether boost facility [10]. This boosting facility, shown in Figure 7, would be a coupled system consisting of a momentum exchange tether for performing the payloads orbital transfer and an electrodynamic tether to re-boost the facility back to its initial orbit.

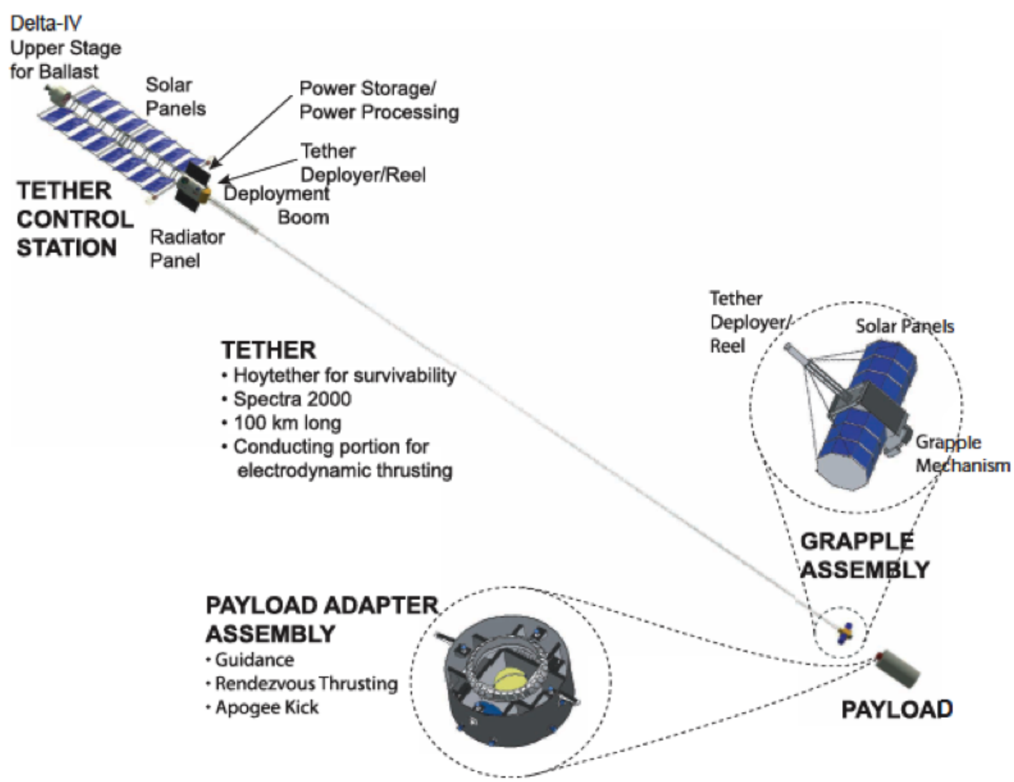


Figure 7: Basic Schematic of a Tether Boost Facility [10]

The boost facility design will initially boost payloads from LEO to GTO, with the possibility of upgrading the system to launch payloads to lunar or other planetary destinations in the future [10]. The facility will nominally capture payloads of 2,500 kg from LEO and impart a $\Delta$V = 2.4 km/s for insertion into a GTO [10]. The boost facility payload capability was sized accordingly so that the tether system can be launched on a single Delta-IV Heavy launch vehicle. The total system launch mass is 20,438 kg and the tether length is 100 km, made of braided Spectra 2000 fibers [10].

The tether boost facility is designed to launch multiple payloads, and hence contains an EDT for re-boost capabilities. Nominally, the facility will perform orbital maneuvers for payloads once every month, so the facility needs to be able to re-boost its orbit within 30 days [10]. In order for a boost facility of this size to perform this task, solar panels will provide 100 kW of power to generate tether currents between 15-20 Amps and supply the necessary thrust for recovering the initial orbit [10].

A tether boost facility provides an alternate means of propelling spacecraft into transfer orbits. While the facility needs to initially be launched into LEO, it can then provide a momentum exchange to other payloads and generate the necessary solar power for re-boosting itself to its initial orbit to repeat the process countless times. This tether technology, while it requires an initial investment and precision rendezvous techniques, can provide a regenerable method of spacecraft propulsion. The boost facility described above is modular and can be expanded upon to launch larger payloads into GTO. In addition, this facility can serve as a stepping-stone for lunar or interplanetary missions, requiring less chemical propellant and driving the launch mass and cost of the mission down [10].

According to Robert Hoyt of TUI, a cislunar tether transport system is an application of momentum exchange tethers that would transport payloads between LEO and the lunar surface without the use of propellant. The basic architecture of this system consists of a rotating tether in LEO and another tether in low-lunar orbit. The tether in LEO would rendezvous with the payload and place it into a lunar transport orbit (LTO). The second tether in low-lunar orbit would then catch and deposit the payload in a descent trajectory to the surface. Next, the lunar tether transfers a payload back to the tether orbiting Earth. By transferring payloads of equal mass, the total energy and momentum of the system are conserved and the tether orbits are maintained without the use of propellant [11]. While this transport system is still in the conceptual phase, it is important to note that with current technology capabilities, this reusable system could impart the 3.1 km/s $\Delta$V needed for LTO with a system mass that is only 28 times the mass of the payloads launched ($m_p = 2500$ kg) [11].

Finally, tethered systems can be applied to eliminate space debris, which is becoming an ever-growing concern for future space missions. To clean up space debris using tethers, there are three methods: deployable EDT to produce drag on the satellite during an end-of-life maneuver, capture-toss momentum exchange, or a capture and collect method. Both the deployable EDT and the capture-collect designs are currently funded designs, while the capture-toss method is still a concept design.

Tethers Unlimited Inc. has developed a deployable electrodynamic tether system that autonomously deorbits satellites faster than atmospheric drag. This system would comply with NASAs Safety Standard 1740.14 that establishes guidelines and assessment procedures for limiting orbital debris by significantly reducing the end-of-life maneuver time of a spacecraft [12]. TUIs Terminator Tether design will vary slightly depending on the spacecraft mass and orbit, but a baseline 2500 kg payload in 400 km altitude LEO was analyzed. To deorbit a satellite of this size, a 5 km long tether that is 1% of the spacecraft mass (or 25 kg) can provide the necessary drag to perform the end-of-life maneuver in two weeks [12]. Figure 8 below shows deorbit times using a tether of this size for various orbits. While EDTs provide an effective means for eliminating future buildup of space debris, they do not offer a solution to the debris that is already in orbit around our planet.

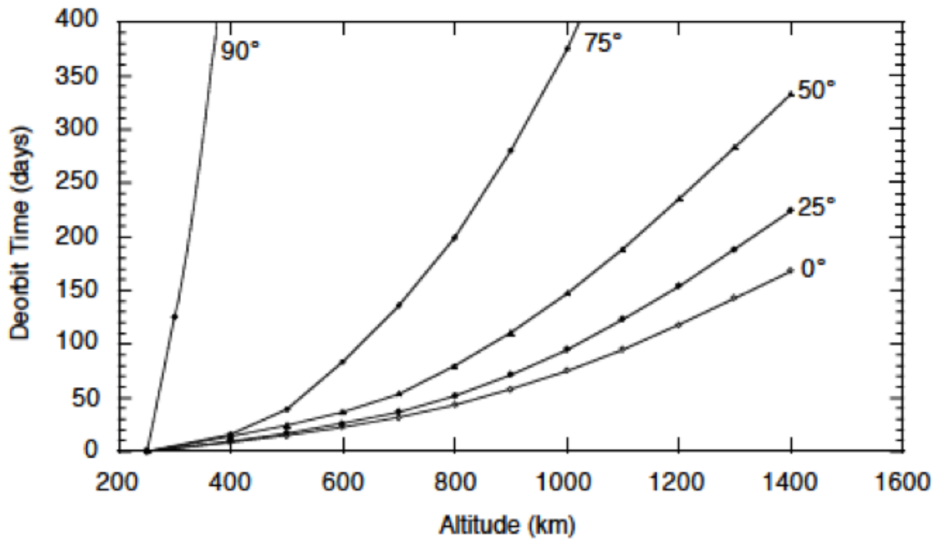


Figure 8: Deorbit Time of a 2500 kg Satellite with a 5 km EDT [12]

Another concept for lessening space debris with the use of tethers involves a momentum exchange tether system. While this system was described in detail above for boosting spacecraft to higher orbits, the same technology could be applied to deorbit space debris. A momentum exchange tether system would be deployed to rendezvous with decommissioned spacecraft. By performing the momentum exchange, the tether system would be boosting itself to a higher orbit and effectively sending the debris on a deorbit trajectory to burn up in Earths atmosphere. In addition, the possibility of coupling a momentum exchange tether system used to boost new payloads to higher orbit trajectories with a momentum exchange of sending decommissioned satellites into a re-entry trajectory (effectively re-boosting the tether system to its initial orbit) is a feasible architecture that eliminates the need for chemical propulsion in two systems.

The final method of eliminating space debris with tethers is through a capture and collect system. Star Technology and Research (STAR) was awarded a grant from NASA in 2012 to complete the manufacture and testing of the ElectroDynamic Debris Eliminator (EDDE) by the end of 2013 [13]. The EDDE system is an electrodynamic tether equipped with solar panels for power and capture nets for collecting debunked satellites that are 2 kg or larger [13]. Over a lifetime of 3 years, STAR proposes its EDDE can capture 136 pieces of space debris in its nets [13]. This 100 kg deployable system offers many advantages over a conventional chemical propellant debris collector including: the ability to change orbit quickly and frequently to collect debris by use of its EDT instead of requiring a propellant impulse for every orbit change, being compact and able to piggyback as a secondary payload due to low mass, and being a reusable system able to collect many pieces of debris. The benefits of this EDDE system make it a very feasible solution for dramatically decreasing the problem of space debris.

# 5 Space Missions With Tethered Systems

The concept of tethering two spacecraft together was first demonstrated by the Gemini 11 and 12 missions in 1966. These two manned missions attached a space tether between the space capsule and the rocket stage to show that operating as a system, Earths gravity would stabilize the two [14]. However, this would be the only instance of tethered spaceflight until 1992 when the Tethered Satellite System (TSS) flew on board the Space Shuttle. Even though tethers were conceptualized and examined for use in space missions during the 60s and 70s, NASA did not examine the feasibility and begin delving into the concept themselves until 1979 [4]. Over the last two decades, tethers have flown on spacecraft and satellites alike. A history of tethers in space is shown in Figure 9.

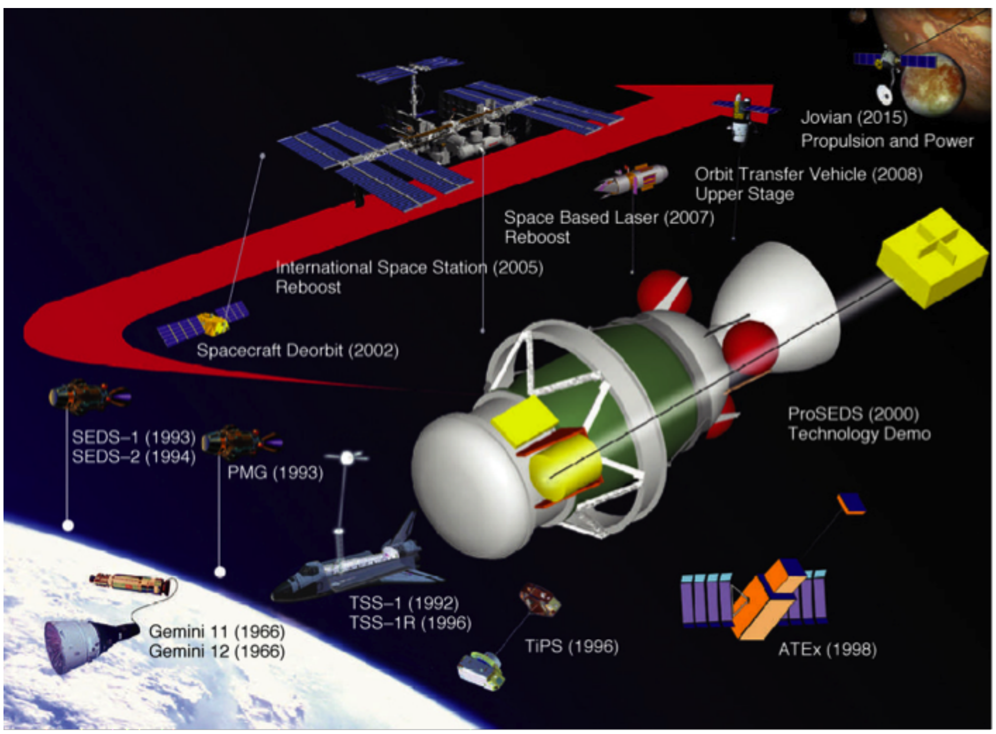


Figure 9: Timeline Outlining the Flight History of Tethers in Space [14]

The two TSS missions are landmarks in the history of tethered spaceflight. These missions integrated a tethered system into NASAs space shuttle orbiter, shown in Figure 10. The goals of the missions were to verify that performance of the TSS payload module in space, determine the forces acting on the tether system to better understand its dynamics, and to develop a firm understanding of tethers for use in planning future tethered missions [15]. Unfortunately, the missions were of little success. The first took place in July of 1992, but ended abruptly when the deployment mechanism malfunctioned, causing the TSS module to only deploy partway. The payload was recovered and flown again in 1996, but in this mission, TSS-1R, the tether snapped after five hours of operation [15]. While the missions collected only a small amount of data about the tethered system, they provided a benchmark in tethered flight after which many future missions would follow suit.

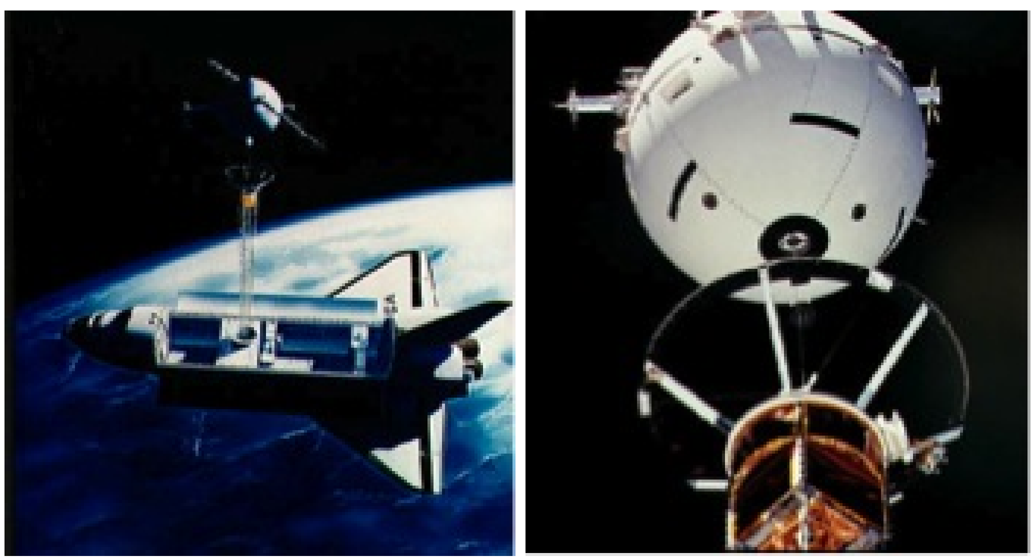

Figure 10: Shuttle with TSS Module (Left) Deployment of TSS (Right) [15]

Following the TSS-1 mission, NASA explored the use of space tethers through the Small Expendable Deployer System (SEDS). The SEDS-1 (1993) mission objectives of deploying a payload on a 20-km tether, demonstrating that the payload could operate on the end of the tether, and examining the reentry of the payload after cutting the tether were all met with success [4]. SEDS-2 (1994) successfully performed a tethered orbital maneuver to change trajectory, although its proposed objective to study the evolution of a tethered system was cut short after five days when the tether was severed by micrometeoroids [4]. Both SEDS missions were instrumental in explaining the effects of tether deployment, expanding our dynamical understanding of tethers.

The Propulsive Small Expendable Deployer System (ProSEDS) was a mission proposed by NASA that was a follow-up to the SEDS missions. This mission was to be the first to use a bare electrodynamic tether to generate significant thrust. The flight-proven SEDS would be launched on a Delta II rocket and used to deploy a 15 km long tether (5 km of which would be bare conducting wire and 10 km of insulated tether) [9]. The electrodynamic tether would generate an average of 120W of power to generate thrust and provide power to the spacecraft batteries for prolonged operations [9]. The demonstration of the success of this technology would be the precursor for installing and EDT onboard the ISS. However, the project was cancelled, and a reboost EDT has yet to be implemented on the ISS.

In the last five years, tethers have been flown on CubeSat missions to demonstrate deorbit maneuvers, study momentum exchange capabilities, and perform station-keeping through EDTs [14]. Electrodynamic tether use for thrust and power in LEO is another area that has seen many recent university-based projects. Other tether projects are also in development by companies such as Tethers Unlimited Inc. for missions involving space debris elimination and orbital boost maneuvers.

# 6 Concerns for Tethers in Space Applications

Many of the tethered space systems that have flown have encountered problems, with few exceptions. A major setback and issue with space tethers is deployment. Numerous tether missions have been unsuccessful due to the failure of the tether to deploy fully. One leading cause is the malfunction of the tether deployment reels during the process of extending the tether. The challenge of deploying a long, thin tether in the presence of gravitational forces is one that has placed major setbacks on the use of tethers on spacecraft today.

Another major concern for space tethers is severance by orbital debris or micrometeoroids. With the increasing concern of space debris, especially in LEO, the probability of a damaging collision is continually escalating. With a thin tether, small impacts with orbital debris can sever the tether, rendering it and the mission terminated. To combat this issue, braided tethers such as the Hoytether have been developed and tested [2]. Small amounts of propulsion have also been flown on the CubeSat missions for small orbital maneuvers to protect the deployed tether.

Finally, dynamical instability can cause tethers to snap and break. The deployment of a space tether must be carefully performed to ensure that the extending tether does not experience amplifying vibrational motion. Tether vibrations can also occur in EDTs with the build-up of electromagnetic interactions on one side of the tether. These vibrational motions must be damped in order to protect the tether from unstable motion that could ultimately compromise the mission. The deployment of tethers, severance by debris, and amplified vibrations are major concerns that have limited the use and success of tethers in space applications due to the inherent delicate procedures that must be rigorously followed for a successful tethered mission.

# 7 Future Ideas for Tethered Space Systems

While the practicality of using space tethers for propulsion cannot be denied, relatively speaking, space tethers are still a new technology, having been used consistently for less than two decades. The dynamics of the tethered space system are still being examined and explored, yet research on these systems has come a long way so far. Some ideas have already been proposed for the future of space tethers. One proposal is to use a tethered system as a space elevator, connecting a satellite to Earth. This synchronous tether that would rotate with the Earth was proposed by Yuri Artsutanov in the 1960s, but his vision is still the focus of many scientists and engineers today [16]. Today, we do not have the materials that would support a structure of this size, but possibly one day in the future. Other elevator-type tethers have been explored, including the proposition of a lunar elevator. Other concepts in the realm of space tethers include skyhooks that could pick up and place objects onto the Moon or other planets using little energy. While the uses of space tethers in the future is unknown, one can be sure that space tethered systems will continue to be used on the forefront of spacecraft and satellite applications.

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