Space Tether and Space Elevator Concepts

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Introduction

The idea of space tethers has been around for over one hundred years. They have long been the topic of science fiction books. With new developments in technology and forward thinking, they have the potential to become reality.

The idea of tether propulsion is to use long, strong strings to change the orbit of a spacecraft. Early tests of this concept have already been completed. The first flight experiment was the Tethered Satellite System (TSS) flown on the Space Shuttle in 1992. The first successful orbital tether flight was on the Small Expendable Deployer System (SEDS)-1 in 1993. Many other tether missions have been flown with varied success. Many researchers are currently focusing their efforts on developing space tether systems.

This paper will discuss many concepts of uses for space tethers, highlighting the Single Stage to Tether (SSTT) system and Space Elevators. There are many technical and societal drawbacks standing in the way of large scale implementation of these concepts that will also be discussed.

Tether Uses

Electrodynamic Tether

An electrodynamic tether uses a conductive material that can act against a planetary magnetic field, generating a current through the tether. This current acts like a dynamo, slowing the thether's orbital velocity. Current flows in an upward direction away from the planet. The mission TSS-1R flew an electrodynamic tether from the Space Shuttle at an orbital velocity of 7 km/s. It was 19.5 km long and produced an electric potential of 3500 V.

If a direct current is applied to an electrodynamic tether, this current exerts a force against the magnetic field. This can be used as a passive propulsion system to accelerate a spacecraft.

Attitude Control – Tidal Stabilization

Spacecraft attitude control can be attained by using a tether utilizing tidal forces. If a tether is deployed from a spacecraft with a mass on the end, the tether will automatically orient itself in a vertical position. The spacecraft on the upper end of the tether will be traveling faster than its natural orbital speed. Centrifugal force will pull it upwards. The lower mass will be traveling slower than its natural orbital speed, thus be pulled downward. This stabilizes the spacecraft in a known attitude.

This method of attitude control is cheap and reliable. It needs only a small amount of fluid that can be expelled to dampen vibrations.

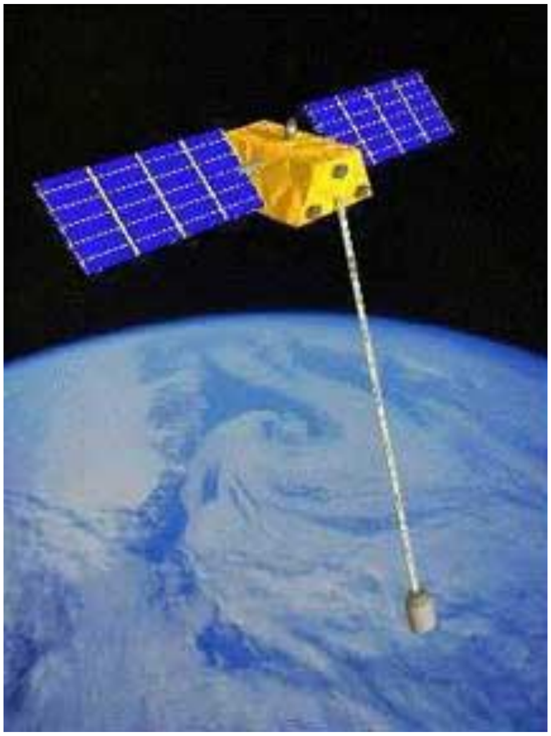


Figure 1. NASA drawing of a satellite utilizing tethered attitude control.

Momentum Exchange Tether

If a long tether is rotating in space and a payload could rendezvous with one end, latch on for a ride, and then release, it will have gained momentum from the tether. This is the concept behind a momentum exchange tether. A rotating tether with tip speeds between one and three km/s is envisioned. The payload that attaches to one end will be accelerated by the tether’s rotation, thus adding velocity (delta V) to the payload. For lunar applications, because there is no atmosphere, the tether tip could actually touch the surface and pick up its payload!

From the law of conservation of momentum, the tether loses momentum while the payload gains it. This means that the tether must be recharged somehow. This can be accomplished by deorbiting old spacecraft. An orbiting spacecraft could be grabbed by a momentum exchange tether and lowered into the atmosphere. The weight of the spacecraft falling to Earth would add momentum to the tether, speeding up its rotation.

Free-Space Skyhook

A free space skyhook is a form of momentum exchange tether that is rotating in empty space. A large tether catches onto its payload and applies its centrifugal force for an amount of time equal to a rotation of 180 degrees. This will result in the maximum delta V that can be imparted on the payload. This maximum delta V will be equal to twice the tip speed relative to the tether center of rotation.

Free-space skyhooks can be used in series to help a spacecraft travel large distances. One tether slings the spacecraft into a coast for some distance where it encounters the next tether that adds its delta V, and so on. A series of two to three free-space tethers could be used for travel from the Earth to the moon. A series of eight could be used to traverse the solar system and even achieve solar escape velocity. Each tether would provide just enough delta V to reach the next.

A system of skyhooks would have no energy loss, thus not need recharging, if the net mass flow is towards the large body. This would be the Earth in the Earth-Moon system, or the Sun in the solar system. If the net mass flow is not in this direction, each tether would need some other sort of device to add rotational momentum in order to keep the system functional.

Non-Thrust Orbital Maneuvers

Non-thrust orbital maneuvers include two masses linked by a tether. This can be used for release or capture. The concept is very well illustrated in Figure 2. The two masses are launched together in a circular (green) orbit. In the figure, they start at the right and travel counter clockwise. As the masses orbit Earth, the tether is deployed. Once completely deployed, the tether is released. The release point becomes the perigee of the upper mass (purple) and the apogee of the lower mass (brown). The orbits of both masses are changed by this maneuver. For a capture, the process is reversed.

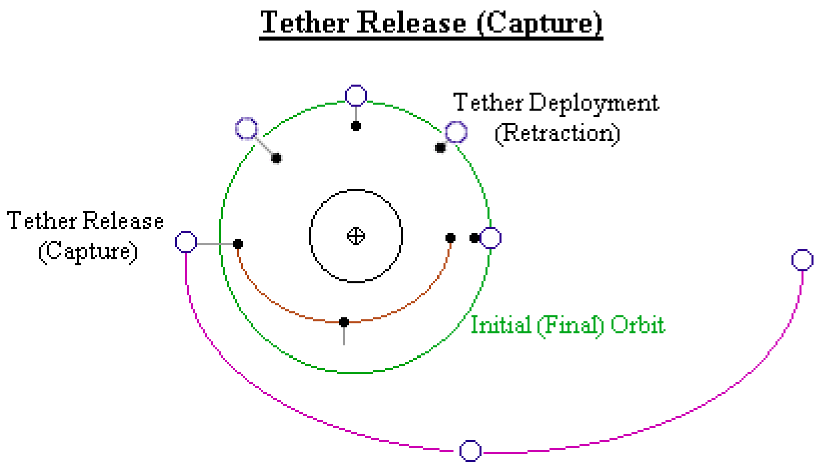
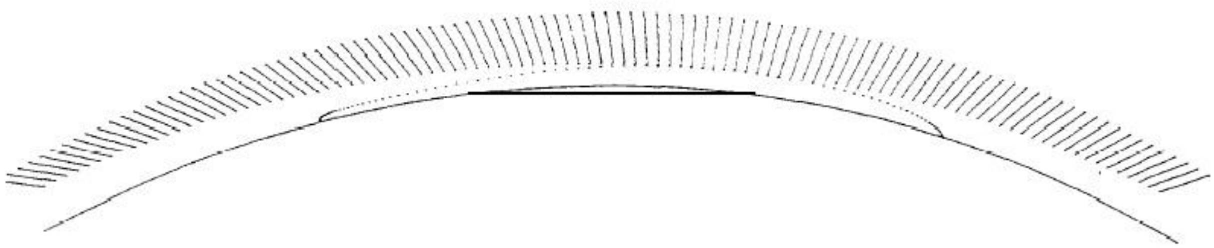


Figure 2. Example of a non-thrust maneuver. Both masses start (or end) together on the green circular orbit traveling counter clockwise (clockwise).

Single Stage To Tether (SSTT)

The idea behind a Single Stage to Tether (SSTT) system is to significantly reduce launch costs using momentum exchange tethers. A long tether, rotating and orbiting Earth (or any other planetary body), picks up a moving vehicle and slings it into orbit. It can also be used to lower an orbiting vehicle into the atmosphere. The momentum exchange tether is in a circular orbit, rotating between 1 and 3 times per orbit. The rotation rate is chosen such that the tip velocity is zero relative to the Earth's surface when the tether is in a vertical position, which is where it will capture its payload.



SST0 launch, sub-orbital payload handoff to baseline 290 km long tether, and lifting reentry. Drawn with Earth and tether to scale, with tether and launch vehicle location shown every 10 seconds (right to left).

Figure 3

A rocket is used to get to a suborbital altitude where the tether rendezvous occurs. For this launch system, the rocket only has to provide about one half of the delta V needed to reach LEO. The rocket can be made totally reusable because it returns to earth on a reentry trajectory. This launch system could theoretically reduce the cost to orbit to six dollars per pound because it allows for a simpler launch vehicle and more cargo. Figure 3 (Oldson and Carroll) shows the exchange from launch vehicle to tether and then the launch vehicle reentry.

The mass of a SSTT system is roughly the square root of a rocket alone. The tether strength requirement is about half that of a space elevator.

A SSTT system designed by Oldson and Carroll in 1995 is studied for further detail. Their optimal SSTT system was found to reduce the delta V required from a launch vehicle by 1.2 km/s. They determined 3 natural sizes of tether systems in LEO. They include a hanging, swinging tether with a length of 25 to 50 km, and can impart a delta V of up to 0.1 km/s. Their medium tether, which completes two spins per orbit, has a length of 290 km, and can impart a delta V of 1.2 km/s. The long tether completes three spins per orbit, has a length of 760 km, and can impart a delta V of 3.4 km/s.

The main facility is placed at the end of the tether opposite the payload capture device. For the medium system, Oldson and Carroll placed the main facility mass at 420 km altitude. This results in a payload capture altitude of 130 km. The total mass of this system includes the mass of facility hardware at 5 tons, capture hardware is 1 ton, and tether is 5 tons. A large ballast on the order of 140 tons would also be needed.

Oldson and Carroll did an analysis on tether expected life span against micrometeoroid hits. Their estimate used the following equation:

$$\text{Tether life (km-yr)} = (D + 0.3\text{mm})^3/4,$$

which was based upon the Spectra tether used on SEDS-2. For the medium 290 km tether studied with an average diameter of 5.3 mm, the expected life is 55 days. For a tether with diameter of 17 mm, the expected life is 4 years. Based upon this finding, they also defined a barely spinning tether as one that rotates once per orbit (relative to tether local vertical). This tether would have a lower number of micrometeoroid hits. When compared to a hanging tether adding the same delta V, the length would be half as long. The thickness therefore increases, leading to 4 times the lifespan while still being 10 % lighter. Compared to the medium tether, the barely spinning tether would be 30 % lighter.

The concept of SSTT could be used in a lunar application. In this case, there is no need for a launch vehicle. Because there is no atmosphere around the moon, the tether could be in an orbit such that the tips touch the surface, where a payload capture could occur. This is a good alternative to rockets for launching objects from the moon. The tether would only require periodic orbital and rotational adjustments. The lunar application is achievable using today's technologies.

For application of SSTT, tether deployment is the first step to establishing the system. To accomplish this, first launch the main facility with tether coiled up inside, into the desired circular orbit with the desired spin rate. Then start the tether deployment with a spring ejection or a thrust maneuver. The tether spin rate must be maintained throughout the deployment by adding spin angular momentum as the length increases.

Capture transients must also be accounted for. Before capture, the tether is at equilibrium, but after capture, it will stretch. This will cause a peak load 70% higher than post-capture equilibrium. This problem drives the tether system size. The main facility contains mostly the winch and storage wheel. It must perform an anticipatory reeling maneuver to counteract tether stretch and cancel out post-capture sag. It is a complicated task to perform this correctly. At release, the system must avoid slack in the tether.

As mentioned above, because the tether is giving momentum to its payloads, it must be re-boosted to maintain orbit and spin rate. The tether's energy comes from its orbital velocity and rotational momentum. Re-boost can be accomplished by shuttling return traffic through de-boosting orbiting spacecraft as detailed earlier. Another recharge method would be an onboard propulsion system, but this adds engine and fuel mass. A third possibility is to use an electrodynamic tether, but this adds mass because it needs a power plant.

Space Elevator

A simple explanation of a space elevator is a tether connected at one end to a planetary body and space at the other. It is powered by the spin of a planet, tapping the planet's angular momentum. Because of this, it needs no recharging. The payload climbs the tether to achieve orbit. This system can be used to transport people, satellites, power, and fuel between Earth and space.

The idea of a space elevator was first conceived of by Tsiolkovsky in his *Speculations Between Earth and Sky*, which illustrated concepts in celestial mechanics. Tsiolkovsky came up with a hypothetical tower stretching from the equator up to tremendous heights. Even he thought of this as completely absurd given the tallest structure of the time was the Eiffel Tower at 300 meters tall.

Y. N. Artsutanov in 1960 wrote that a cable under tension is a much simpler structure. He showed that one could deploy two cables from a satellite in a synchronous orbit, extending one end towards the Earth and one end upward to lift the satellite with orbital centrifugal force. If both cables are deployed at equal rates, the forces zero out. Then this deployment is continued until one end reaches the surface. At this point the outer end of cable will be at 150,000 km altitude. Tidal force will keep the structure stretched and vertical. Then the bottom would be anchored to the ground and a counterweight added to the upper end to pull on the cable and thus the anchor. This keeps the cable in tension.

The tensioned cable can support elevator cabs. Cabs going to GEO can let go in the center, having gained their energy in part from the climb and in part from Earth's rotation. Cabs going past GEO gain their energy from centrifugal force, powered entirely from Earth's angular momentum. Cabs going the full 150,000 km would have a velocity of 11 km/s, which is enough energy to reach Saturn's orbit on a Hohmann transfer.

The tether would need to take the form of a distorted bell curve which is narrow at the ends, tapering to a maximum area at GEO. The taper ratio is exponential in weight to strength ratio. So, a steel cable must be 10^{50} times bigger in the middle than at the ends, and it must weigh 10^{52} times what it can support. This simple calculation lead to early proofs that space elevators on Earth are impossible. Advances in technology have created the possibility of smaller, more realistic space elevator designs. Obviously today there are much stronger materials available, but none yet strong enough to support a space elevator system.

There is a growing interest in the research community and in the general public on the subject of space elevators. Many privately funded efforts are currently under way. The estimated cost for development of a space elevator system is around $1 billion. The estimated cost for construction is about $10 billion.

There are many aspects of this problem currently being researched. One is the study of system dynamics. On small-scale dynamics, researchers are looking into degradation of tether components at an individual fiber and interconnect level including fiber breakage. On large-scale dynamics, things being looked at include system oscillations, tether profile variations, and tether system responses. Other areas of research include tether degradation from atomic oxygen, debris, electric and magnetic fields, radiation, orbital dynamics, and thermal load effects. Also issues of radiation effects when transporting humans. The cab will either need to climb quickly or provide shielding for passengers.

Drawbacks and Areas for Research

The idea of using space tethers was long though of as impossible and was ignored for many years. Scientists and the general public typically laughed off their possibilities. It hasn't been until the last ten years or so that the concepts have started to be taken seriously.

The primary issue today is the production of materials strong enough to support these applications, but light enough to make their applications possible. For the space elevator, the tether must have tensile strength f up to 100 GPa . Much research is focused on this issue. Carbon nanotubes have been created with strengths of 200 GPa and weigh much less that of steel. A cable of carbon nanotubes the thickness of a thread could hold the weight of a large automobile, but they cannot yet be manufactured in large quantities to be useful for space tethers. However, currently available materials can be used for Mars and Moon applications.

Another material issue is that single strand tethers are quickly cut by micrometeoroids. The lifetime of a single strand with a length of 10km is only 5 hours, which is not useful for long term applications. Dr. Robert Hoyt proposed using a cylindrical net, such that cut strands' strains are redistributed as shown in Figure 4. Called Hoytethers, the life spans are on the order of tens of years.

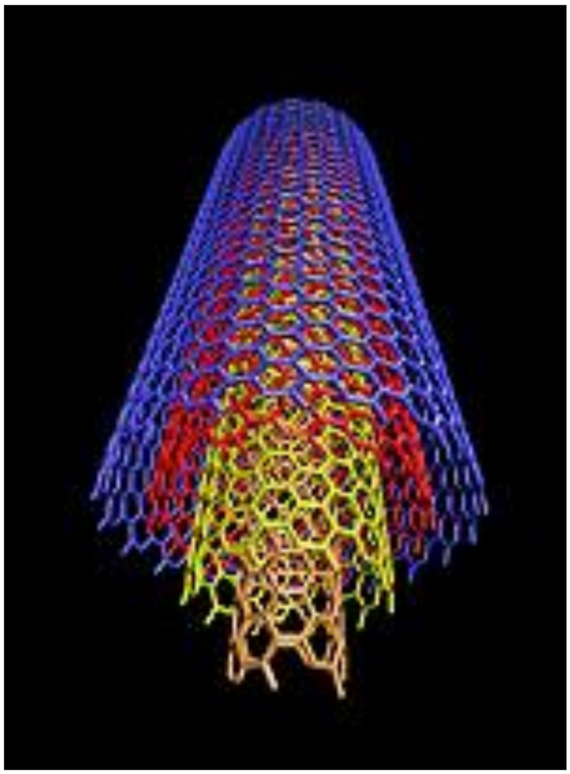


Figure 4. Carbon nanotubes in fence-like structure which can reduce the impact of micrometeoroid hits.

There are also many safety issues that need to be addressed. Space tethers are big, and whip around at orbital velocities, creating many dangers. There could be catastrophic results of a tether failure. In many cases, the lower half crashes to Earth creating large impact areas. A tether failure within a few kilometers of a payload or humans will cause significant risk from recoil and entanglement.

Some other problems that must be overcome are currently being researched. Including the fact that ultra-high strength plastics must be coated for protection from UV radiation and erosion from molecular oxygen. Material overheating can cause tether failure or damage because a thin tether in space has little heat radiation capability. There are rendezvous problems and other technical issues that need to be worked out. Failure to capture can be catastrophic. Also, handling equipment mass is high because a long tether system will need complex controls to dampen vibrations, and long tethers are not easily maneuverable. Tether deployment is also an issue, because half of the tether missions to date have failed in deployment. Finally, navigational calculations are complex, involving tether stretch, payload sequences, solar wind, aging structural material, docking, docking failures, energy adjustments, collision hazards, etc. Each of these things must be worked out before any space tether system can become a reality.

Conclusion

There are many applications for space tethers, some of which have already been tested in Earth orbit. The use of space tethers could significantly reduce the costs of space travel. Space tethers can be used to grab suborbital spacecraft and boost them into orbit, greatly reducing launch costs. Once there, other tethers could be used to transfer the S/C anywhere in the solar system. The possibilities are endless.

Recent developments in materials engineering have made many space tether applications possible. However, much research still needs to be done to achieve materials that can meet other application needs, including the space elevator.

The use of tethered propulsion, including space elevators may not only be the dream of science fiction writers. Research is being done to figure out how to overcome known drawbacks. Although possible, a lot of work is required to make tether propulsion and space elevators reality.

List of Sources

Bankston, Cheryl D., John A. Gilbert, and Dennis R. Wingo. *Tethers and Their Role in the Space Exploration Initiative*. Proceedings of the 3rd International Conference on Engineering Construction and Operations in Space III. May 31-June 4, 1992, Denver, CO.

Cate, Vincent. SpaceTethers.com. 2003.

Cosmo, Mario L. and Enrico C. Lorenzini eds. *Tethers in Space Handbook*. Third Edition, NASA/OSF, 1997.

Edwards, Bradley C. *The Space Elevator Development Program*. IAC-04-IAA.3.8.2.01. 55th International Astronautical Congress 2004, Vancouver, Canada.

Harvard-Smithsonian Center for Astrophysics. *Special Projects Group Web Site*. http://cfa-www.harvard.edu/~spgroup/

Lemley, Brad. *Going Up*. Discover Magazine Vol 25. No. 07. July 2004.

Moravec, Hans. *Orbital Bridges*. The Robotic Institude Carnegie-Mellon University. Pittsburgh, PA. 1986.

Oldson, John and Joseph A. Carroll. *Potential Launch Cost Savings of a Tether Transport Facility*. AIAA Paper 95-2895, 1995.

Spaceelevator.com. *What is a Space Elevator?* 14 April, 2006.

Watanabe, Susan ed. *NASA – Space Transportation With a Twist.* http://www.nasa.gov/vision/universe/roboticexplorers/tethered_spacecraft.html. 25 February, 2006.

Wikipedia.com. *Tether Propulsion*. 14 April, 2006.