Space Tethers

Matthew Sandoval

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1. Introduction

Bringing down the cost of space launches has been an important goal throughout the space industry. Many solutions have been proposed including privatizing the space industry to allow for open market prices, the use of reusable launch vehicles, and other promising technologies. A fairly new technology being developed that shows promising results is the use of space tethers. A space tether is a long strand of fibers used to couple a space craft with another mass which allows for an exchange of momentum or energy. Tethers can be used to change the orbits of satellites without consuming any propellant, or to transport payloads from a planet to low altitude orbit. Space tethers are still in the early stages of development; however the idea has many promising features. Like many technologies, space tethers are limited by current material strength properties. This paper outlines space tether applications as well as their potential advantages and shortcomings.

2. Types of Space Tethers

There are three main types of space tethers, momentum exchange, electrodynamic, and electrostatic tethers. Each type of tether has an individual purpose. This section outlines the three major types of space tethers, their proposed functionality and the problems associated with each.

2.1. Momentum Exchange

2.1.1. History

The idea of changing the orbit of a payload without consuming any propellant originated in the late 1980's. Dr. Robert Hoyt proposed his idea of using a long, thin, high strength tether in orbit around a massive body to alter the trajectory of a payload. Hoyt's proposal consisted of deploying a tether and sending it into an elliptical orbit around a massive body. It would be timed so that the tether was aligned in a radial direction at perigee. A spacecraft could then rendezvous with the lower tip of the tether at this point. A half rotation later the spacecraft would separate taking with it some of the tethers orbital energy and momentum, sending it into a higher energy orbit. This assembly is now referred to as a rotovator and is shown in Figure 1.

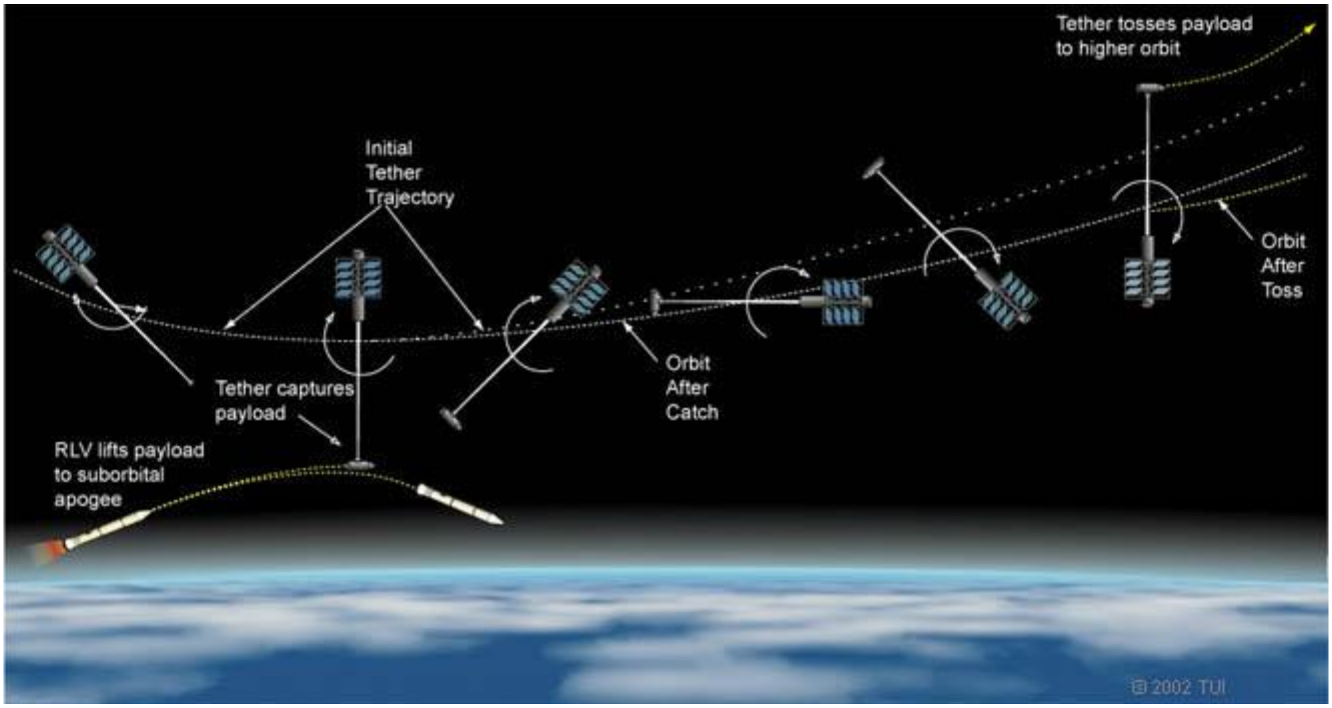

Figure 1: Tether Capture and Release Process

2.1.2. Deployment

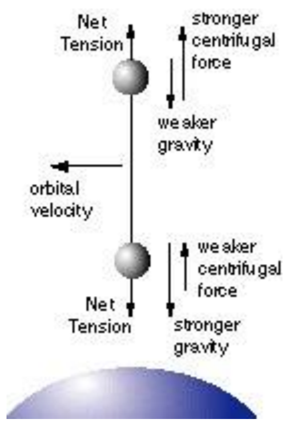

Figure 2: Force Diagram

A momentum exchange tether is a long thin cable used to couple two objects in space. This coupling allows for both momentum and energy to be exchanged between the two objects. The tether is deployed by releasing or pushing one object away from the other. Once the objects are separated, the difference in the gravitational force at the two locations will pull the objects apart. The two objects will continue to separate until they reach an equilibrium position where the net force on one object balances the other. The forces acting on each object are the gravitational force and the centrifugal force. The centrifugal force will dominate the object in higher orbit and the gravitational force will dominate the object in lower orbit. A tether in such equilibrium is said to be gravity gradient stabilized, and the tether aligns itself in the radial direction of the body it is orbiting as shown in Figure 2.

2.1.3. Stationary Tethers

A stationary tether is deployed by releasing a spacecraft payload from a launch vehicle. The center of mass of the tethered system would continue to orbit around the massive body while the tether would try and align itself in a radial direction due to the gravity gradient field. When the tether is fully deployed it can be severed to provide an orbital boost or a means of de-orbiting. The tether is in equilibrium however the equal but opposite forces acting on the objects creates tension in the tether. Severing this tether allows for this tension to be released, and results in an orbital increase of the higher mass and an orbital decrease in the lower mass. A stationary tether has the property that if the tether is severed, a half period later the separation distance between the two objects is seven times greater than the initial separation distance. This separation gives the upper mass a boost allowing for an increase in orbital energy, and decreases the energy of the lower mass, allowing it to de-orbit.

2.1.4. Rotovators

A rotovator is a long high speed rotating tether. Similar to the momentum exchange tethers described above, a rotovator is a tether in which the center of mass is in low altitude orbit. The difference is that rotovator is not gravity gradient aligned, but is allowed to rotate while in orbit. The length of these tethers can vary. They can either be relatively short in which a spacecraft in LEO can rendezvous with one tip as it rotates, or they can be long enough to reach the surface of the massive body where it would latch on to a payload. This has the significant advantage of being able to launch payloads from the surface of a massive body into orbit without consuming any propellant. Rotovators are also capable of capturing a payload in orbit and safely transporting it to the surface of a body without expensive de-orbiting maneuvers. The orbit of a rotovator can be designed to be circular and have multiple contact points on the surface, or elliptical having one rendezvous point at perigee. The tether is rotated at a high rate, giving the tips a significant velocity. The velocity of the tips is equivalent to the delta V provided by chemical rocket engines in conventional propulsion. This velocity would be a combination of the tethers orbital speed and its rotational rate. A schematic of the rotovator system is displayed in Figure 3.

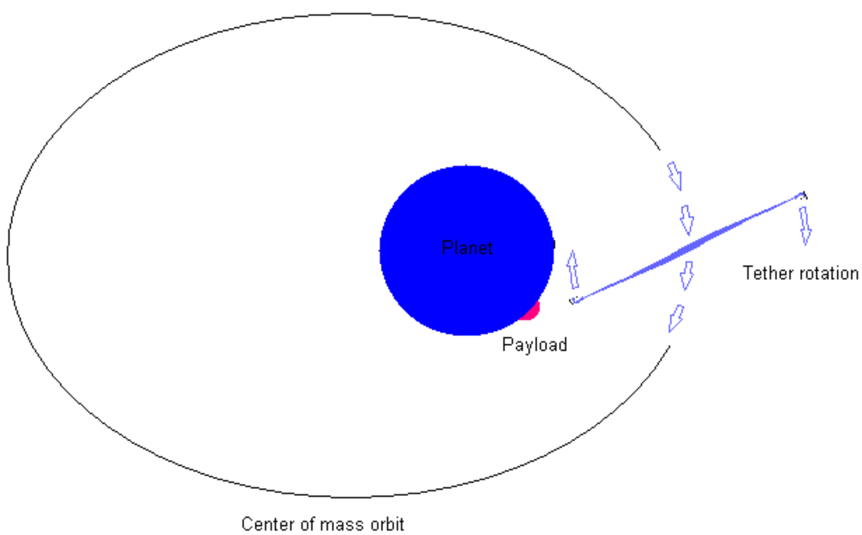

Figure 3: Rotovator Example

2.1.5. Space Elevator

A space elevator is a long stationary tether which has its center of mass in geosynchronous orbit and reaches down to the surface of the orbiting planet. The orbit must be geosynchronous to ensure that the lower tip of the tether remains fixed at a single point on the surface. The purpose behind the space elevator is to overcome a massive body's gravity without expending any propellant. This system relies on the use of an externally power motor to climb the tether and release the payload near the upper tip. Although current materials do not allow for the construction of a space elevator on Earth, they are possible on smaller airless bodies such as the moon. Since the center of mass must be in geosynchronous orbit, the tether must extend well beyond geosynchronous altitude. In an effort to reduce the length of the tether, a counter weight can be used as shown in Figure 4.

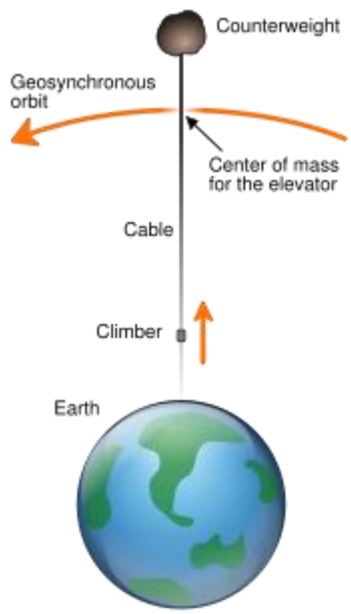

Figure 4: Space elevator Schematic

The space elevator also loses a portion of its momentum when the payload separates from the tether. Over a number of launches, the orbit of the tether will decrease unless this momentum is recouped. In order for the elevator to remain in geosynchronous orbit, the mass flux up the cable must equal the mass flux down the cable. Various methods have been suggested on how to accomplish this. One idea is to have a way of capturing large space debris near the top of the tether, and have in sent down the cable.

Space elevators have the huge advantage of reducing the cost of space launches within a few percent of current conventional propulsion. The concept is great; however it is not practical at this time. We are limited by current material technology and the tendency of the space industry to stick with proven technology.

2.1.6. Design Concerns

Space tethers are still in the early stages of development and there are many issues that need to be addressed. The biggest issue concerning momentum exchange tethers is materials technology. Space elevators require materials with extremely high tensile strength and relatively low density. Studies have shown that a space elevator around Earth would require tensile strengths much higher than current materials technology allows for. One proposed solution to this is carbon nanotubes, also a relatively new technology. The theoretical tensile strength and density of this material would be well above what is required for a space elevator on Earth. Until this or other material technologies are developed further, a space elevator on Earth is not practical. Another concern with momentum exchange tethers is the momentum lost after the payload is tossed into a higher orbit. A portion of the tethers orbital momentum and energy is transferred to the payload as it is tossed. This results in a decrease of the tethers orbit. It is important for the tether to maintain its orbit, therefore after an exchange is made, the tether must have a method to re-boost. A number of ideas have been proposed on how to accomplish this, the most promising being the use of conducting tethers that interact with the Earth's magnetic field to produce a restoring force. These tethers are referred to as electrodynamic tethers.

2.2. Electrodynamic

An electrodynamic tether is a long conducting cable extending from a spacecraft. Various methods of driving current through the tether allows for an interaction with the Earth's magnetic field. Depending on the direction of the current, the host spacecraft will either experience an orbital boost or a drag force.

2.2.1. Electrodynamic Tether Drag

A tether deployed from an orbiting spacecraft will be aligned vertically due to the gravity gradient field. In an electrodynamic tether drag system, the tether has the ability to collect electrons from the ionosphere plasma at the lower tip and emitting them at the upper tip. This creates a current along the tether which interacts with the Earth's magnetic field. The result is a Lorentz force that acts in opposition of the motion of the tether. The Lorentz force is

$$F = J \times B$$

Where J is the current in the tether and B is the magnetic field. The gravity gradient field acts to align the tether vertically, or perpendicular to the magnetic field lines. By use of the right hand rule the cross product of the Lorentz force acts to oppose the motion of the tether. When a spacecraft nears the end of its lifetime, an electrodynamic tether can be deployed, resulting in a simple, inexpensive way of de-orbiting.

2.2.2. Electrodynamic Propulsion

In the same way electrodynamic tethers are used to de-orbit a spacecraft, they can also be used to provide thrust, thus increasing the orbit of a satellite. This can be accomplished by reversing the current through the tether. The Lorentz force also applies, the only difference is the current is sent in the opposite direction, from the orbiting spacecraft to the lower tip of the tether. This can be accomplished by collecting electrons from the ionosphere plasma at the satellite and emitting them at the tip of the tether, or by generating current on the spacecraft using solar panels. This current would be sent through the conducting tether, thus creating a force in the direction of motion of the spacecraft.

2.3. Electrostatic Tethers

High energy particles emitted through solar rays, solar storms and other processes are often trapped by the Earth's magnetic field in a region called the Van Allen Belts. The Van Allen belts contain intense radiation that can be extremely harmful and detrimental to both humans and space instruments. Expensive measures have to be taken to shield components from this high flux of energetic particles. Even with protective shielding, a components lifetime is limited due to the steady degradation of the shielding from these high energy particles. A solution to this problem has been proposed which consists of using a tether held at extremely high voltage to scatter these high energy particles and remediate the radiation.

3. Applications

3.1. The Cislunar Tether Transport System

A tether system has been proposed for payload transfer from LEO to the surface of the moon. This system consists of a tether in an elliptical, equatorial orbit around Earth which would capture a payload in LEO as outlined above. The payload would then be tossed into a medium energy lunar transfer orbit. The payload would then rendezvous with a rotovator or lunavator, which would transport the payload to the surface of the moon. This process is shown in Figure 5.

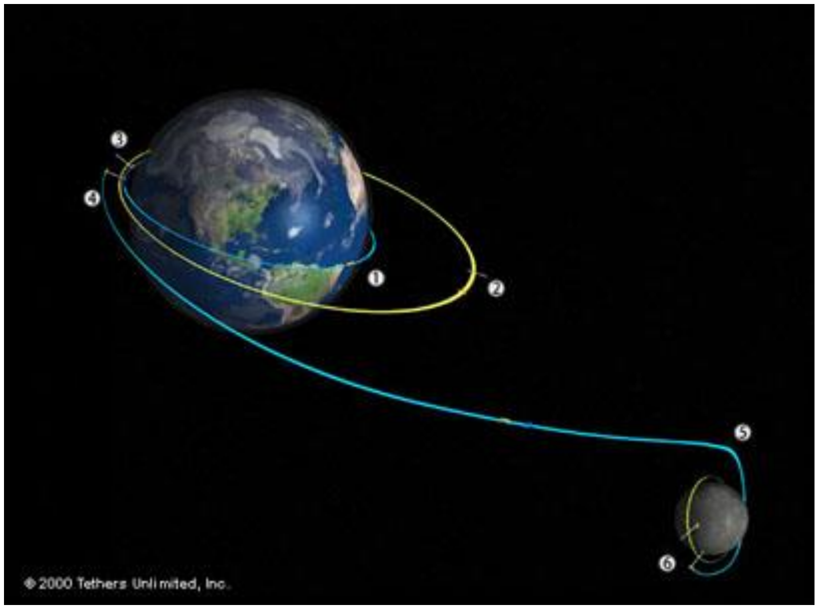

Figure 5: Cislunar Tether Transport System

Preliminary studies have shown that a rotovator in LEO can provide payloads with a total delta V of 2.3 km/s. It is known that a delta V of 13.1 km/s is needed for transfer from the surface of the Earth to low lunar orbit. However if a conventional chemical launch vehicle is used to transport the payload to LEO, the remaining delta V required to reach the moon is approximately 2.1 km/s. The delta V provided by the tether is sufficient for this maneuver. This application could prove to be very beneficial for the colonization of the moon. The delta V provided by the tether would greatly reduce the cost of sending many supplies to the lunar surface. One concern that has yet to be addressed is the need for a negative delta V to circularize the orbit around the moon to allow for rendezvous with the lunavator. The maneuver from LEO into lunar transfer would not require any propellant, however the negative delta V required to circularize the orbit would most likely come from a chemical motor. This propellant used for this maneuver however would be insignificant compared to the savings the tether system would provide.

3.2. High Voltage Orbiting Long Tether System (HiVOLT)

HiVolt is a proposed tether system that would allow for the radiation remediation of the Van Allen Belts. The idea is to have long conducting tethers that extend into the radiation belts. The tethers would be charged and maintained at a very high voltage. This would scatter the energetic radiation particles, forcing them to leave the radiation belt. Unlike previous examples, this type of tether has no propulsive use. They are specifically designed to rid the radiation belts of the high energy particles that cause damage to both astronauts and space instruments. Preliminary analysis and computer modeling showed that the HiVolt system would be capable of reducing the MeV flux of high energy particles in the inner belt to 1% of its natural level within two months. A schematic of the process is shown in Figure 6.

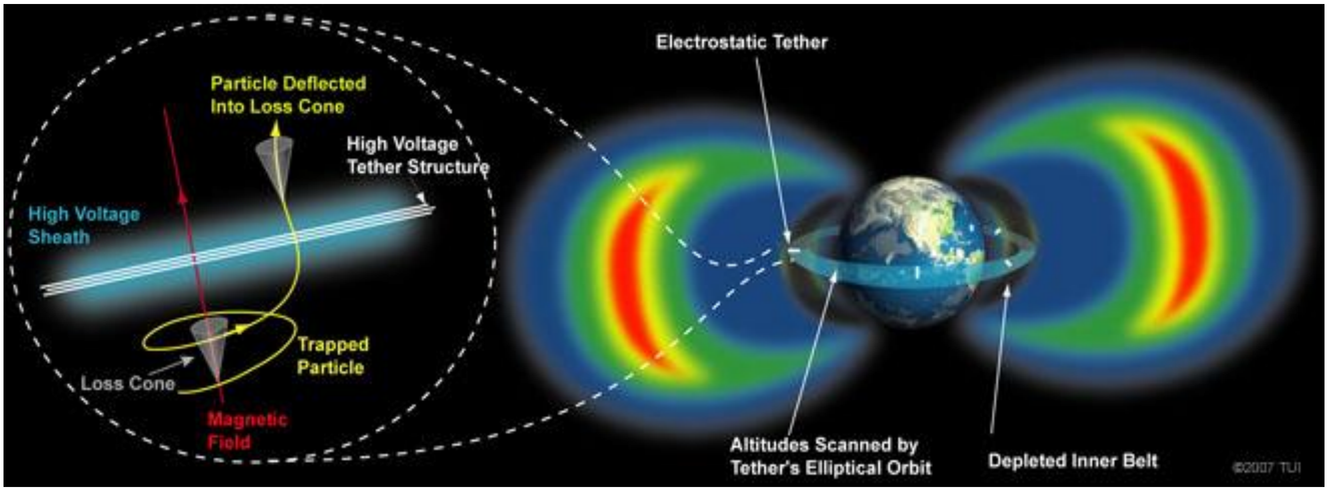

Figure 6: Radiation Remediation Process

A computer model was developed to help visualize the effects of such tether systems. Figure 7 shows flux intensities without remediation during a time in which two solar flares inject the belts with energetic particles.

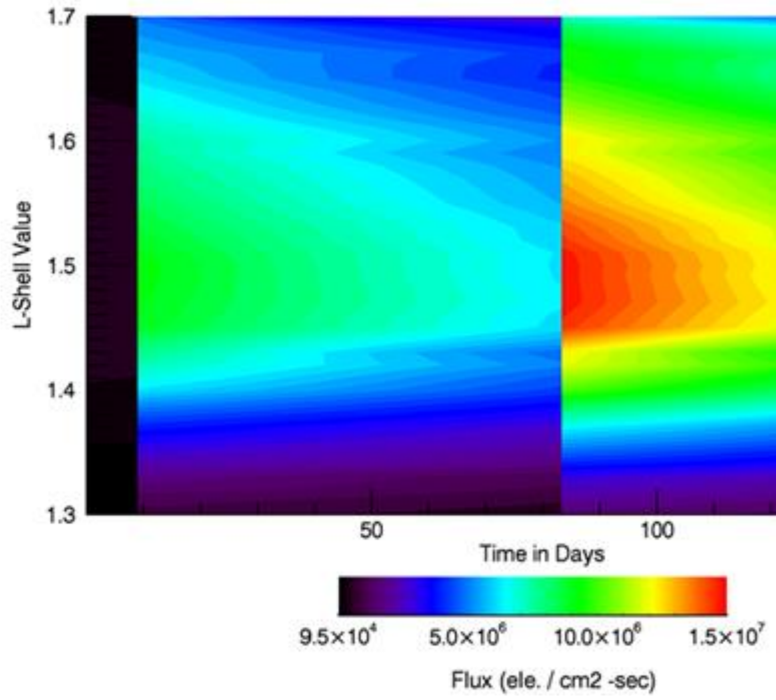

Figure 7: Radiation Belt Flux Intensities Without Remediation

Figure 8 shows the flux intensities under the same conditions but with remediation.

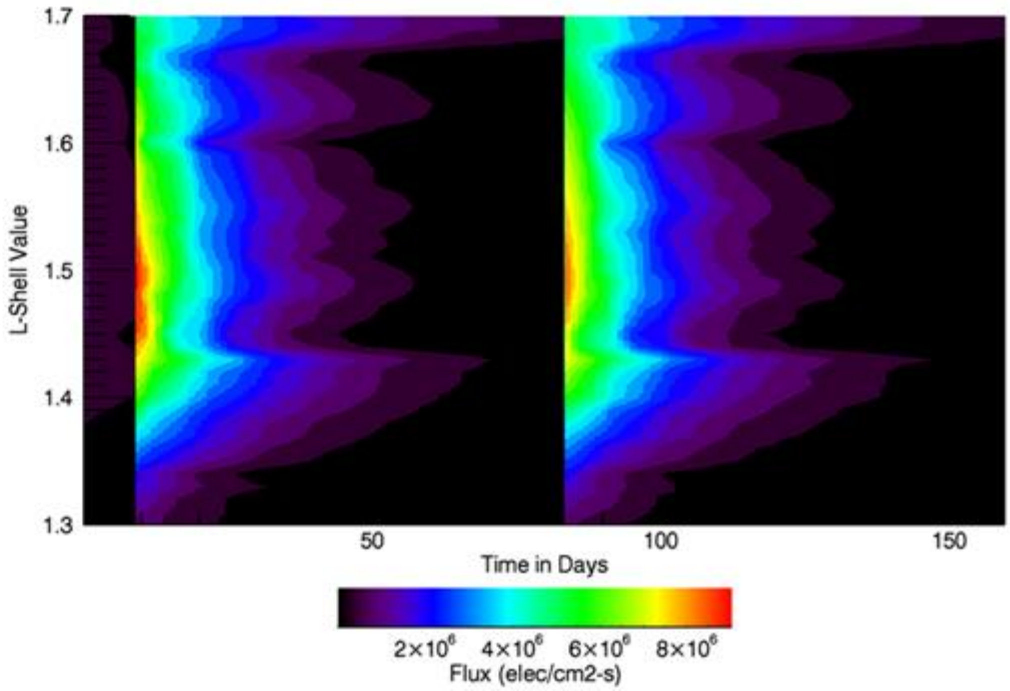

Figure 8: Radiation Belt Flux Intensities With Remediation

This simulation was conducted using a system of 25 electrostatic tethers. It can be seen from the two figures that the results of the HiVOLT tether system would be great. Drastically reducing the flux of energetic particles in the inner belt would greatly improve the safety of astronauts and satellite hardware in orbit. The results have great advantages; however this application might not be very practical. The proposed HiVOLT system consists of 25 2kW tethers that extend into the inner radiation belt. Design, construction, and implementation would be an extremely expensive endeavor.

3.3. Terminator Tether System

A tether system has been developed that can be deployed from a spacecraft nearing the end of its lifecycle. The Terminator Tether System uses electrodynamic drag principles to de-orbit the satellite. The tether was designed in the hopes of mitigating the increasing amount of space debris. The US Space Command currently tracks over 6000 orbiting objects, of which only about 300 are operational. The increasing amount of space debris will soon prove to be problematic, especially for satellite constellations that require strategic placement. The Terminator Tether System was designed to simply bolt to a spacecraft before launch. The system remains dormant until it receives a signal to deploy when the spacecraft is nearing the end of its life. A 5 to 10 km long conducting tether would then be deployed. The passive interaction with the Earth's magnetic field induces a current in an upward direction. This causes a J x B force that acts to oppose the motion of the spacecraft, thus reducing its orbit. A schematic of this system is shown in Figure 9.

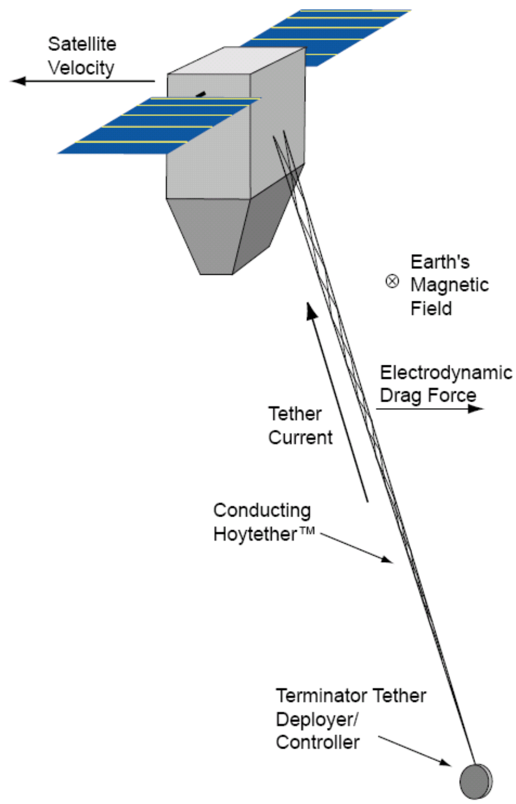

Figure 9: Terminator Tether System

The electrodynamic drag force is relatively small and this process of de-orbiting could take up to a few weeks. There are no time restrictions and this method is more cost effective than using conventional propulsion. This particular tether system could prove to be important in the efforts to keep Earth's orbital space clear of unused debris.

4. Materials

Due to the enormous strain on the various types of space tethers, it is important to select a material that has a very large tensile strength, but must also be relatively light weight. Tether designs can also exceed 150 km in length; therefore manufacturing these systems also has to be feasible. As mentioned above, a space elevator on Earth is not possible with current material technology. The one material that shows promise is carbon nanotubes, which are also still in the early stages of development. Space elevators are however possible to design for smaller, airless bodies such as asteroids and the moon. Studies have shown that materials such as Kevlar or Spectra 2000 which has a tensile strength of 3.25 GPa and density of 0.97 g/cc would be suitable for a space elevator on the moon. A few single line tethers have actually been deployed and a common problem has been damage to the tether from micrometeorites and small space debris. Many tether experiments have been cut short due to the tether being severed by a micrometeorite shortly after deployment. A solution to this problem has come from the design of the

Hoytether. The Hoytether has multiple interlinked lines which gives it the ability to localize any damage obtained from a micrometeorite. This design is shown in Figure 10.

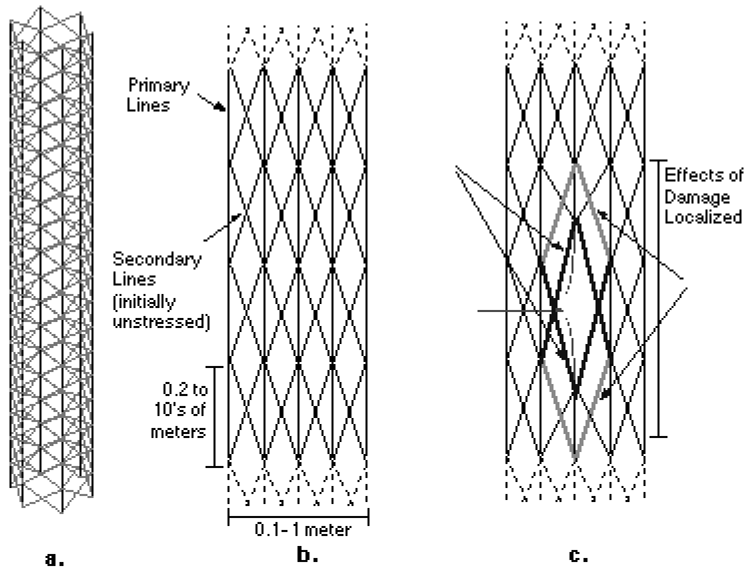

Figure 10: a) Section of tubular Hoytether b) undisturbed Hoytether c) localized damage

Analytical models have shown that this type of design would allow the tether to have a lifetime of tens of years, whereas it has been shown through experiment that single line tethers only have lifetimes of a few weeks. Electrodynamic tethers do not require as high tensile strength as previously mentioned tethers however they must be made of a good conducting material. Lithium and sodium have two of the highest specific conductivities; however they are not very dense and have low conduction/cross sectional area ratios. The best material for electrodynamic tethers is copper.

5. Conclusion

The concept of space tethers has many advantages, the most important being the ability to vastly reduce the cost of space launches by conventional propulsion techniques. This has been a goal of the space industry for years; however there has been no feasible solution. There are many variations of space tethers, but they all have one thing in common, they provide satellites with propellantless propulsion. Momentum exchange tethers can be used in several different ways, whether it is using the tethers tension to raise or lower the orbit of a satellite, or climbing a tether to overcome a body's gravity. Electrodynamic tethers can interact with the Earths magnetic field to provide propellantless thrust and drag. And although electrostatic tethers do not have any propulsive principles, they can prove to play an important role in making space a safer place by remediating the radiation in the Van Allen Belts. The possibilities of these concepts are great, however many of them are not practical. The cost associated with designing, manufacturing and implementing these systems is enormous. The one system that shows results in the near future is the use of electrodynamic tethers as means to de-orbit a satellite, reducing the amount of space debris. More extensive studies have to be performed before any other tether systems discussed here can be made a reality.

References

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