SPACE TETHERS: APPLICATIONS AND IMPLEMENTATIONS

An Interactive Qualifying Project Report

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by

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ABSTRACT

A space tether is a conducting cable attached to a spacecraft that can be used for a variety of purposes such as supplying power to the spacecraft, raising or lowering its orbit, or transferring payload from Earth to high altitude orbits at a significantly lower cost than with conventional methods. This project examines several different types of space tethers with the object of trying to identify the ones with the greatest promise for future applications. It identifies the Momentum Exchange Electrodynamic Reboost (MXER) tether as a concept with a rich variety of applications that is worth studying further for the impact it is likely to have on future space missions.

PREFACE

This IQP, which analyzes the functionality, construction, limitations, and applications of space tethers, is part of a larger group of space policy IQPs that are being conducted during the 2006-2007 academic year. This project is an outgrowth of an earlier IQP on the Space Elevator, which may be regarded as an extreme kind of space tether. Even though this IQP is concerned with a technical subject, it is presented in such a way that it should be accessible even to those without any specialized knowledge of the field. The project focuses mainly on a particular type of space tether – the Momentum-Exchange/Electrodynamic-Reboost Tether, which is a hybrid of the two main types of space tethers: the Momentum-Exchange Tether and the Electrodynamic Tether. After outlining the basic concepts underlying the different types of tethers, this IQP examines those current and future applications that are likely to have the greatest impact on future space missions. This project could be used by future IQP teams as a starting point for an in-depth examination of other issues involving the space tether concept.

ACKNOWLEDGEMENTS

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1 Project Overview

A Space Tether is a long cable that connects two masses and uses fundamental laws of physics to generate electric power, artificial gravity, and thrust or drag, among other things[1], all without using propellant. The concept of the space tether has been around for over a century, and was conceived by a Russian scientist named Konstantin Tsiolkovsky in 1895.[2] Much later, in 1979, the science-fiction writer Arthur C. Clark described Space Elevators in his novel, The Fountains of Paradise.[3] Tsiolkovsky, and a few others after him, such as Giuseppe Colombo, theorized that a large structure could be built that would extend from the surface of the Earth to height above geostationary orbit and could be used as a convenient means of transporting objects from Earth into space. These seemingly far-fetched theories were the basis of the concept of the modern Space Tether. The two most common types of Space Tethers are the Momentum-Exchange Tether (MXT) and the Electrodynamic Tether (EDT).

The Momentum-Exchange Tether is a long, thin cable that attaches two masses together in space and is capable of imparting momentum to objects that come within its grasp. This cable has a large mass on one end and is intended to be deployed into orbit around Earth. The cable will have to be extremely resilient and therefore will be made out of either high-strength synthetic fibers such as Dyneema or carbon nanotubes.[4] Dyneema is based on an ultra-high molecular weight polyethylene, which is fifteen times stronger than steel (~1.2 GPa) and 40% stronger than Kevlar (~3.6 GPa). Carbon nanotubes are recently discovered allotropes of Carbon that have a cylindrical shape at the molecular level, resulting in novel properties such as a tensile strength of around 63 GPa. The material of the MXT needs to be strong in order to perform its main function: grasp an incoming payload and send it into higher orbit. This can be done by timing the MXT's orbital motion and rotation so that it will be oriented vertically when a payload is moving towards it from the Earth. The tether will grab the payload and, after half a rotation, release it into a higher orbit.[5]

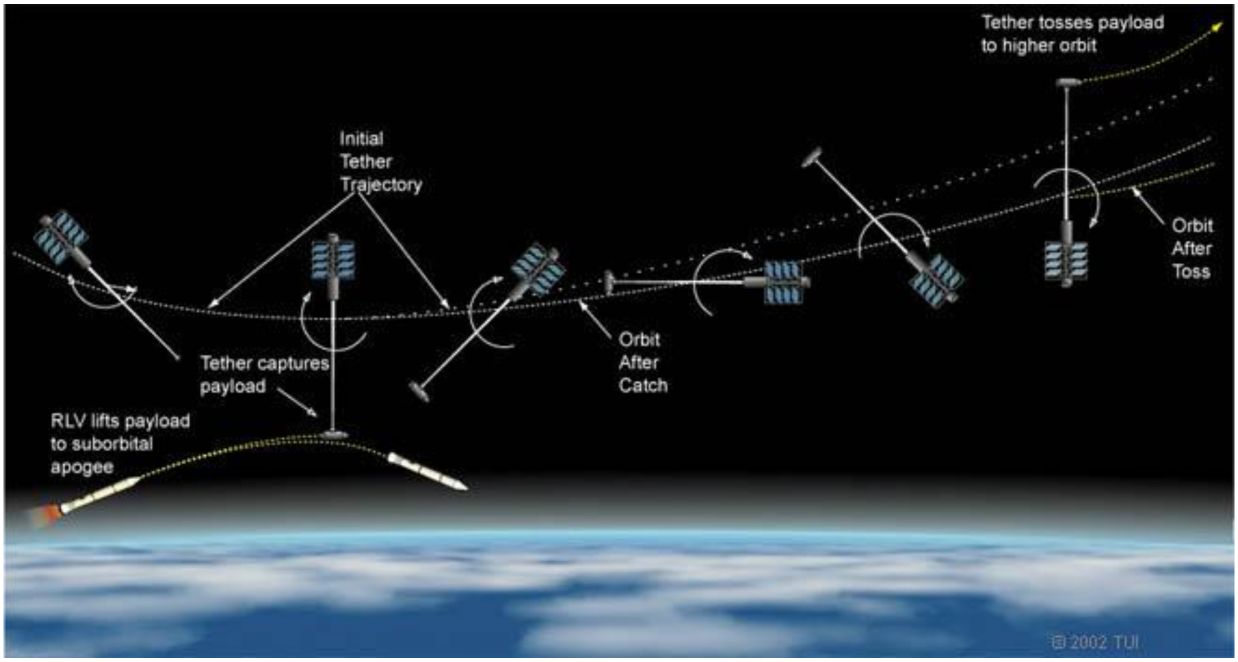

FIGURE 1: MOMENTUM EXCHANGE TETHER OPERATION[5]

The limitations of the MXT are that the material of the tether needs to be extremely strong, the cable is susceptible to being cut by micrometeoroids, and the capture of the payload needs to be perfectly timed. As mentioned earlier, an MXT must be strong enough to withstand the stresses it is likely to experience during operation. Micrometeoroids are small pieces of debris that fly through space that could sever and destroy the tether of the MXT if they come into contact with it. Another major concern is the aiming of the payload at the tether and the timing with which it is grasped must both be very precise. If a payload were to miss its exact destination on the tether, it could be lost completely, or, in the worst-case scenario, it could crash into the tether and destroy both objects.

The Momentum-Exchange Tether has some applications that could benefit both the technical and commercial communities. One scientific application is the concept of a lunar or interplanetary transport system that requires very little propellant. The “Cislunar Tether Transportation System”, conceived by Dr. Robert Hoyt of Tethers Unlimited, Inc., is an example of such a system where one tether in Earth’s orbit will toss a payload to lunar transfer orbit, where another tether in lunar orbit will catch the payload and deliver it to the surface of the moon.[5] A commercial application of the MXT is to provide a cheap and efficient way to launch satellites into space, most likely Low Earth Orbit (LEO). Tethers can theoretically reduce the cost of launching spacecraft into LEO by more than 50%, making it possible for communications companies to launch satellites in a much less expensive manner, or for them to launch more satellites overall.

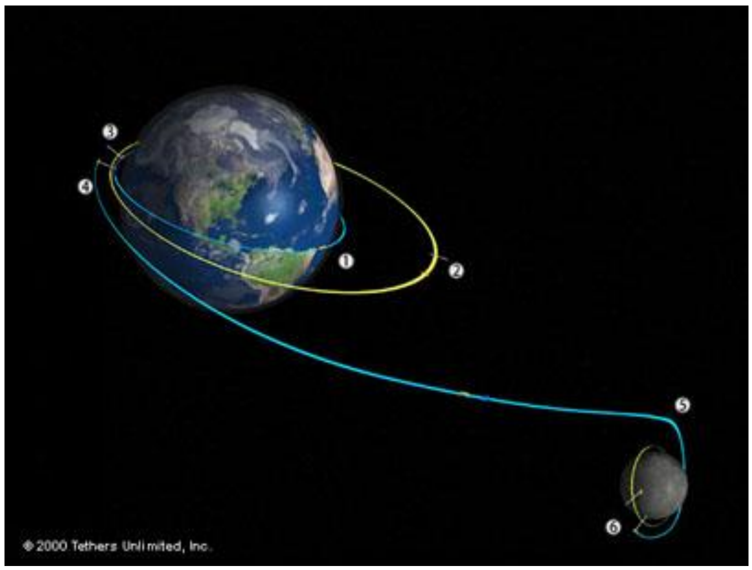

FIGURE 2: THE CISLUNAR TETHER TRANSPORT SYSTEM[5]

(1) A payload is launched into a LEO holding orbit; (2) A Tether Boost Facility in elliptical, equatorial Earth orbit picks up the payload (3) and tosses it (4) into a lunar transfer trajectory. When it nears the Moon, (5), a Lunavator Tether (6) captures it and delivers it to the lunar surface.

An Electrodynamic Tether is a long, conducting wire that extends from a spacecraft. The fact that the tether itself is a conductor means that it will have a voltage induced in it as it moves through the Earth's magnetic field. When a conducting wire is moved through a magnetic field, an electromotive force (EMF) develops across its ends as a result of Faraday's law of induction.[16] The EMF causes a current to flow through the wire, with the ionospheric plasma providing a closed loop outside the wire. The current in the wire interacts with the Earth's magnetic field to produce a drag on the wire. To create thrust, a battery is added to the circuit which is able to overcome the induced current, therefore creating a force in the opposite direction.[1]

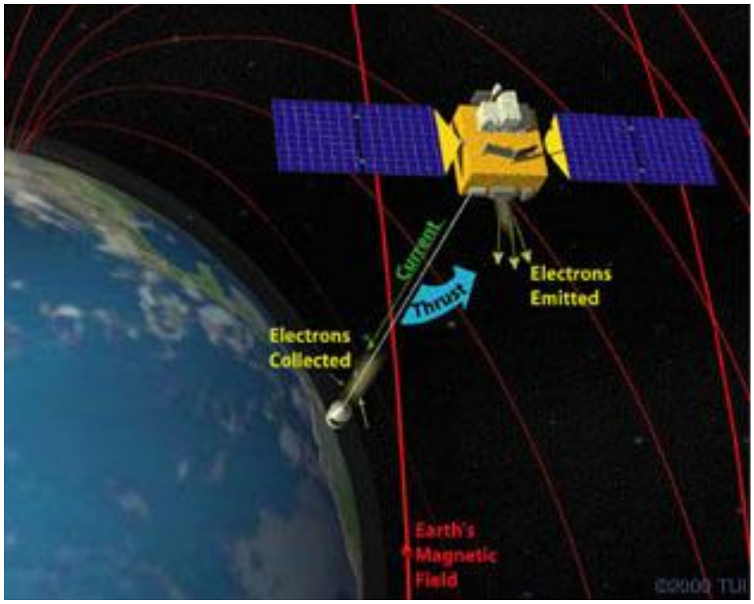

FIGURE 3: PRINCIPLE OF ELECTRODYNAMIC TETHER PROPULSION[5]

One limitation of the EDT is that the induced current creates many vibrations in the tether. If these vibrations are not damped, they could grow so large that they eventually wear down the tether from mechanical stress. Another limitation is the possibility of high current surges through the tether, which could cut it or damage its electronics.[4]

The preceding explanation of EDTs hints at some of their possible applications. EDTs are able to create electrical power and thrust or drag just from moving in Earth's orbit. One of the major applications of EDTs is power generation. Spacecraft and space stations, like the International Space Station (ISS), can use EDTs to generate power that they can use onboard. A 20-km tether in LEO, for example, has the potential to produce up to 40 kilowatts of power, which is enough to run manned facilities in space.[1] Another potential application that employs the ability to create drag force is attaching an EDT to a satellite so that at the end of its life, it can easily fall through the Earth's atmosphere and be burned up, instead of floating around in LEO as space debris. A possible application of the thrust generating ability of an EDT is to keep the ISS in orbit in a cost effective way. In the current design, the ISS needs about 77 tons of propellant to keep itself from lowering its orbit. If it had been built with an attached EDT, it would only need about 17 tons of propellant or less to be able to stay in orbit, depending on how much power the EDT is using.[1] This would cut the cost of keeping the ISS and other spacecraft or space stations in orbit by a significant amount.

The focus of this project will be on the hybrid combination of both the Momentum-Exchange Tether and the Electrodynamic Tether called the “Momentum-Exchange/Electrodynamic-Reboost” (MXER) system.[5] This combines the best of both types of tethers to create a cheap and effective upper stage launch station. The MXER uses the Momentum-Exchange properties to catch and release spacecraft, while subsequently using the Electrodynamic properties to create thrust that can restore its orbital energy after a payload transfer. The electrical current that will be run through the wire to react with the Earth’s magnetic field can be supplied using solar power, and is estimated to have a recharge time of a few weeks, making it possible to have monthly trips to the Moon.[7] The National Aeronautics and Space Administration (NASA) is currently doing research on the concept of the MXER and once it is launched, the system will extend a 100 to 120 kilometer long tether. The tether would be made out of a high-strength, yet lightweight material, part of which would be an insulated conductive metal that would allow the current to flow.[6] If this system is used, there is no need for an upper stage vehicle, substantially reducing the cost to launch the spacecraft. The major challenge to achieving an EDT is finding a material that is both conductive and strong. Once this concept is realized, though, it will have great economic benefits and could help boost the ability to further travel through and explore space.

2 MOMENTUM-EXCHANGE TETHER

2.1 FUNCTIONALITY

The primary function of a Momentum-Exchange Tether (MXT) is to transfer a given amount of momentum and orbital energy from the MXT to a spacecraft, launching it into a higher orbit. This is accomplished by using the principle of conservation of angular momentum. The MXT would be orbiting the Earth in LEO, with a perigee of 300-500 km and an apogee of 5000-8000 km. A typical payload would be launched into a circular orbit around Earth at an altitude of 300-500 km, enabling it to rendezvous with the MXT when it is at perigee. This is the fundamental idea that makes the momentum-exchange possible, since the specific energy (energy per unit mass) of an orbiting object is proportional to the distance between its perigee and apogee. Thus, a MXT in a 400 x 8000 km orbit has much more orbital energy per unit mass than a payload in a 400 x 400 km circular orbit and can transfer energy to it without having its own orbit severely modified.[17]

As the tether passes through perigee, it will be at its greatest orbital velocity and will be moving faster than a spacecraft in a circular orbit at the same altitude. For example, if the tether is moving at a speed of 8.9 km/s at perigee, a spacecraft in circular orbit would be moving at a speed of 7.7 km/s at the same altitude. In order for the tether to “catch” the payload effectively, it needs to be rotating about its center-of-mass at the rate that would force its tip velocity equal to the difference between its center-of-mass velocity and the velocity of the payload; since the rotational motion of the tip is opposite to the motion of the payload, the relative velocity of the tip and payload is then zero and a smooth catch can be effected. It is required that both the relative position and relative velocity of the tip of the tether and the payload be zero at the moment of the catch.[17]

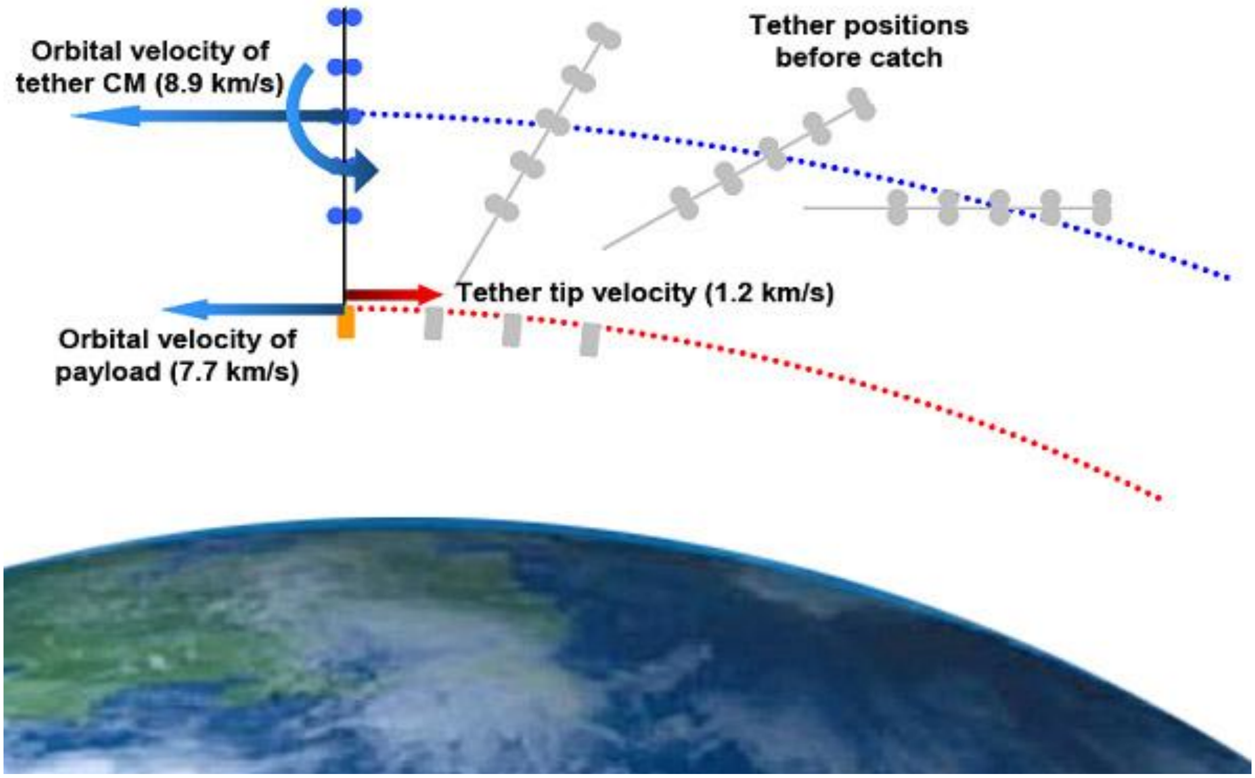

FIGURE 4: TETHER TIP APPROACHING PAYLOAD BEFORE RENDEZVOUS[17]

Once the payload is caught by the tether, it begins to be accelerated centripetally by the tension in the tether. The MXT loses energy and assumes a lower orbit, while the payload gains energy in the process. The payload gains a velocity equal to twice the velocity of the tip, and this gain is almost instantaneous (and faster than conventional chemical upper stage propulsion).[17] In this case, the payload would gain 2.4 km/s in velocity, which is a typical ΔV requirement for a geosynchronous transfer orbit (GTO) through perigee burn.[21] The catch mechanism is placed at the tip of the tether so that there is room for some error in the process. One concept involves a hook on the payload that latches on to a net-like structure at the end of the tether.[17]

2.2 Construction

With the current construction concepts, the tether facility would consist of a rotating, 100-120 km long tether with a variety of masses and other mechanisms in place along its length. The tether tip would have a mechanism that would assist in hooking up the tether to a suitable payload aimed at it. The other end of the tether would consist of a ballast mass, which would probably be the spent stage of the launch vehicle that would put the MXT into orbit before any use of it can be made.[17]

The 100-120 km tether would be a composite material with an extremely high tensile strength that is then coated or treated in some manner to protect the tether from ultraviolet radiation and atomic oxygen. The material used would most likely be one of two materials: Dyneema or carbon nanotubes. Carbon nanotubes are one of the strongest and most rigid materials known to mankind in terms of both tensile strength and elastic modulus. In 2000, a multi-walled carbon nanotube was tested to have a tensile strength of 63 GPa. This can be compared to high-carbon steel, which has a tensile strength of only about 1.2 GPa.[18] Carbon nanotubes also have a very high elastic modulus, up to 1 TPa, and their specific strength (tensile strength divided by density) is 1.3-1.4 g/cm^3, giving them the best specific strength of any known material. Dyneema, comparatively, is a readily-available synthetic fiber with a high tensile strength that has been in use since 1979, when it was invented. Dyneema, formally known as Ultra-High Molecular Weight Polyethylene (UHMWPE), has some defects that may limit its use in atmospheric or near-atmospheric temperatures as its melting point is only about 144 degrees Centigrade, while its use is not recommended above 100 degrees Centigrade.[12] Carbon nanotubes seem to be the safest and strongest choice, but the cost of a tether of such size constructed out of a new and untested material make some engineers uneasy.

The tether would be constructed using a multiple strand, cross-linked configuration that would be able to provide levels of redundancy for the tether modules should any event occur in which portions of the tether were damaged or severed. Possible agents that cause this damage will be discussed in a later section of this chapter. Part of this high-strength tether, about 40-80 km in length, could be integrated with a conductive material, such as aluminum, that would allow for the tether to conduct enough electrical current to power control modules and mechanisms along the tether that do not require a greater deal of power. For mechanisms requiring larger amounts of power, smaller spacecraft-like units would collect solar power and deliver it to them in the form of electrical current.[17]

2.3 Limitations

While carbon nanotubes provide a high-strength material from which the MXT can be constructed, space debris and other hazards can compromise the security and integrity of a tether structure that is permanently in orbit above the Earth. Micrometeoroids currently pose the greatest threat to space tether structures and the space tether itself. These small particles of rock, which usually weigh only a gram or less, pose a major threat to not only the tether, but to space exploration in general. This is already evident from the care that NASA expends in organizing spacewalks from the ISS. Small particles are extremely common in space and their velocities relative to spacecraft in orbit are on the order of kilometers per second.[15] According to the *Space Tethers Handbook*, typical micrometeoroid velocities are about 20 km/s, with an average density of about 0.5 kg/m^3. At impact speeds above the speed of sound, solids become compressible and the shockwave due to impact produces effects analogous to those of an explosion.[20] To put the large number of micrometeoroids around the Earth into perspective, it is estimated that micrometeoroids comprise most of the 30,000 tons of space debris that impact and deposits itself upon Earth every year.

The strength of the materials used in the space tether's construction is generally tested as the length of the tether is made longer and longer. There exists no better real world testament to the damage that can be inflicted by micrometeoroids than in SEDS-II, 1994, where an important experiment which tested the second longest structure ever deployed in space was cut short during the extended mission phase when a micrometeoroid cut the tether at the 7 km point. Even when the thickness of a tether is increased beyond 10 mm or more, depending on the altitude, the risk does go not down much. Even with a decrease in micrometeoroid risk, the debris risk dominates and the tether is likely to fail if any part of the debris passes near the center of the tether.[20]

In terms of survivability of a space tether, the TiPS (Tether Physics & Survivability) program was organized to research just such a question. Their findings, while limited because of time and financial constraints, nevertheless suggest that a tether technology could be successfully deployed in space for future operational missions.[20] However TiPS notes that considerable technological development will still be required before an operational system can be field tested.

2.4 Applications

The main application of the Momentum-Exchange Tether is as one of the primary components of the MXER (Momentum Exchange Electrodynamic Reboost Tether). Since the MXT loses some orbital energy in the process of throwing a payload into higher orbit, it must be re-energized so that it remains in the same orbit and may be used multiple times. The best way to do this is to incorporate the electrodynamic reboost properties (described in more detail in the next chapter) into the design, enabling it to be re-used as many times as needed. The ideal application of the MXER is to provide an extremely inexpensive way for payloads to be launched into higher orbit (mainly GTO to GEO) from LEO. The details of the MXER will be discussed in a later chapter.

Another possible application is the Station Tethered Express Payload System (STEPS), which can provide a way to get back small payloads from the ISS without having to use rockets. A payload would be tied down inside a mini capsule that can be ejected downward through a robotic airlock. Then, a 30-33 km tether would deploy from the capsule and orient the capsule for reentry. The tether is eventually cut and burned up in the atmosphere.[20] The technology used in this application was proved to be possible by the NASA-sponsored Small Expendable Deployment System (SEDS-1) in 1993.[19] Many other applications like this, involving the transfer of payloads, are possible with Momentum-Exchange Tethers.

3 ELECTRODYNAMIC TETHER

3.1 FUNCTIONALITY

An Electrodynamic Tether, or EDT for short, is a long conducting wire extended from a spacecraft, such as a satellite. The gravity gradient field, sometimes referred to as the tidal force, will tend to orient the tether in a vertical position. Orbiting around the Earth, the EDT will cross the Earth's magnetic field lines at a velocity of approximately 7-8 km/s.[23] A diagram of the EDT in orbit around the earth, including the Earth's magnetic field lines and orbital paths according to current polarity, can be seen below in Figure 5.

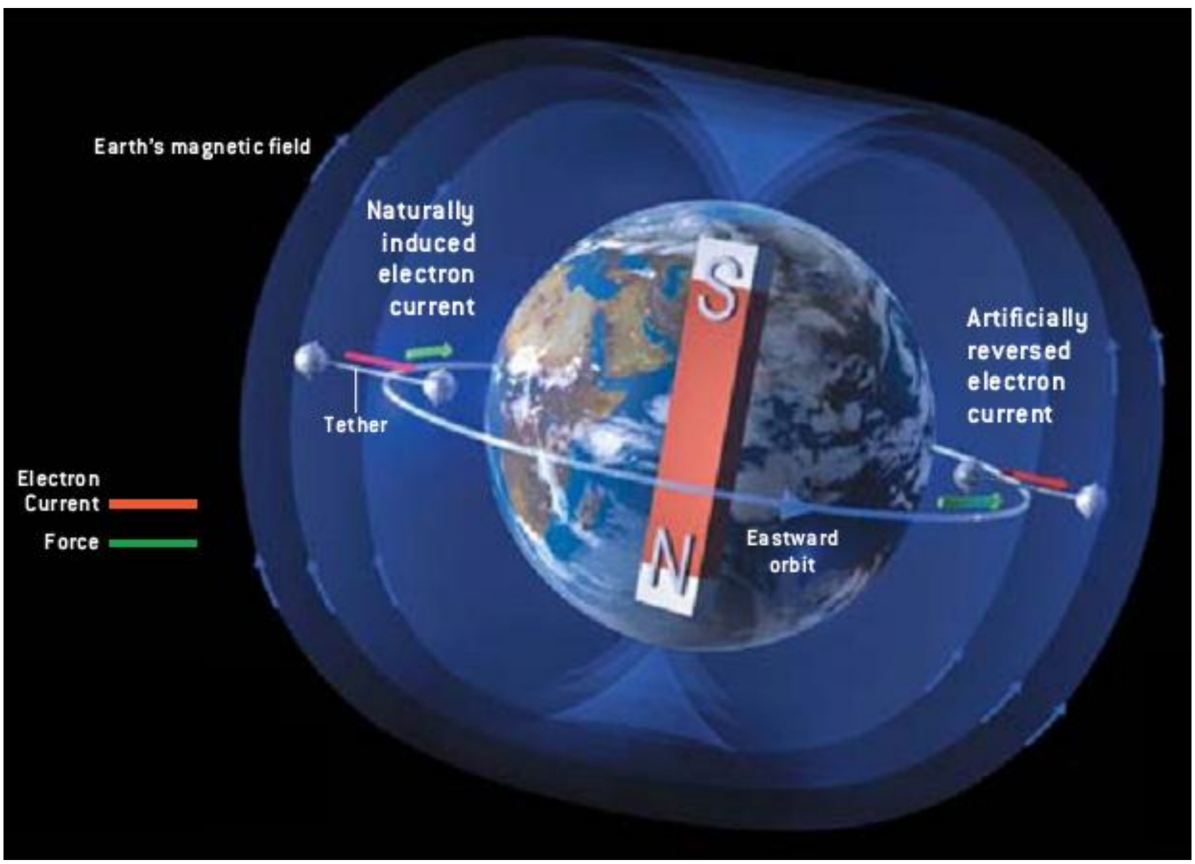

FIGURE 5: EDT ORBIT ACCORDING TO CURRENT POLARITY[1]

While EDTs have multiple uses, one of their principle functions is to generate electric current that can supply power to a satellite for on-board experiments or other purposes. The motion of the tether through the Earth's magnetic field causes a **v**X**B** Lorentz force[23] on the electrons in it, causing an electron current to flow in the tether towards the planet (with the charged ionosphere outside providing a closed loop for the current). The current flowing in the tether causes it to experience a **JXB** force from the Earth's magnetic field that retards its motion and causes it to slow down. The EDT thus acts as an electromagnetic brake that exerts a drag force on the satellite and slows it down, causing it to drop to a lower orbit. This is illustrated in Figure 6.

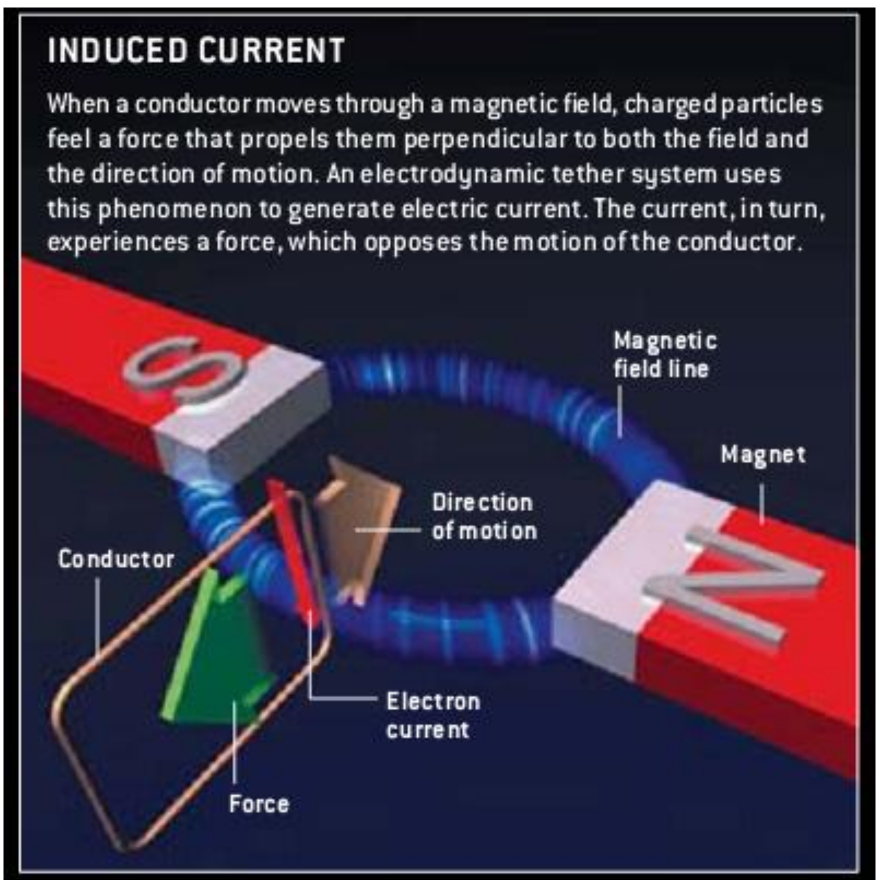

FIGURE 6: HOW INDUCED CURRENT PRODUCES DRAG[1]

This change in orbital altitude can be reversed when a battery is added to the circuit of the EDT. This battery can overcome the induced current and reverse the current's direction, as seen in Figure 7.

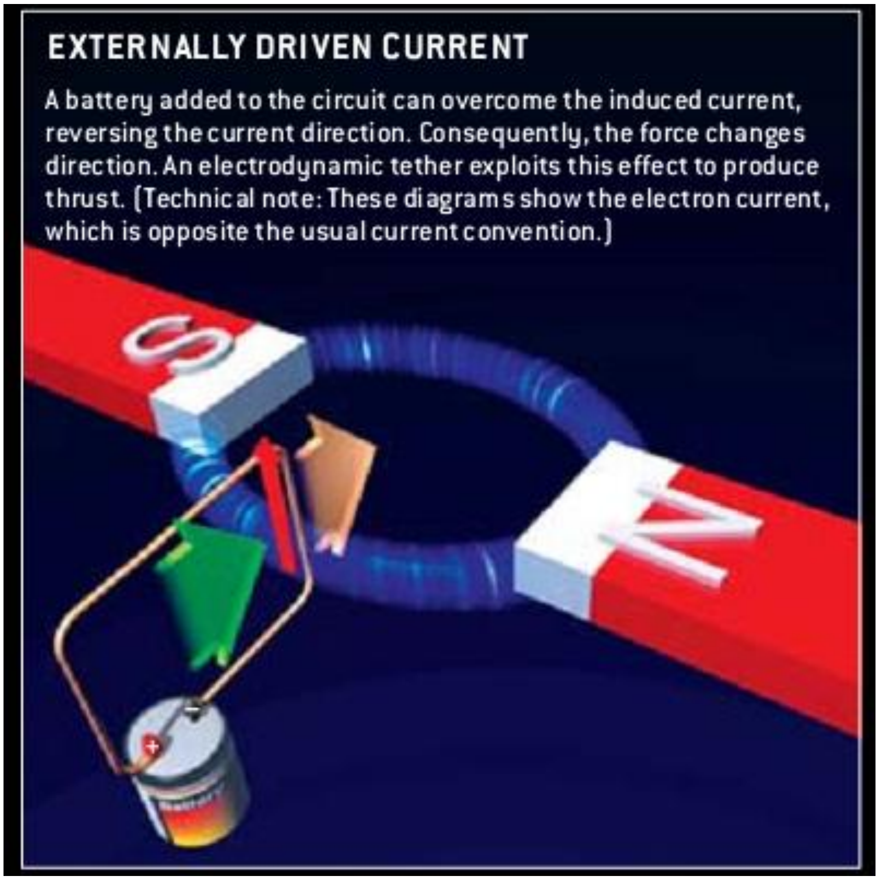

FIGURE 7: HOW ADDING A BATTERY WILL COMBAT DRAG[1]

The forces the tether experiences are now in the same direction as the EDT's motion. This changes the tether's orbital altitude by raising the tether.[22] The advantage to raising the orbital altitude of the tether is to reboost a tether facility that incorporates momentum-exchange principles, also known as a MXER, back to its original orbit. The specific applications of the MXER tether will be discussed in a later chapter. The principles discussed in this section were proven by the NASA-sponsored Plasma Motor Generator (PMG). The PMG was a tethered mission that successfully used a 500m Electrodynamic Tether to convert orbital energy into electrical energy, and raise and lower its orbit.[25]

3.2 Construction

The basis of an Electrodynamic Tether is the insulated, conductive wire that enables current to flow through the length of the tether. Theoretically, any kind of conductive material would work, but aluminum, copper, and silver fibers are most commonly used. The length of an EDT is primarily determined by the function it is intended to serve.

An EDT designed to de-orbit a 1000-2000 kg spacecraft would probably be about 5-10 km long and would have a mass of 15-30 kg (typically around 1% of the host spacecraft). The tether would be wound on a spool and is deployed at a rate of several meters per second, once the spacecraft has reached the end of its life.[24]

To power a manned space station would require an EDT of about 20 km in length. This tether could provide upwards of 40 kW of power, which is enough to run most research facilities in space.[23] Like the EDT designed for de-orbiting a satellite, this would attach to and deploy from a spacecraft in a similar manner. Unlike the previous type of EDT, however, it would stay deployed throughout the life of the space station similar to a solar array, generating power at all times as it passes through the Earth's Ionosphere.

An EDT can also be integrated into a Momentum-Exchange Tether to create a MXER tether facility. The total length of the tether would be 100-120 km long, 40-80 km of which would include a conductive wire, which would enable the reboost of the facility.[17] The specific construction of the MXER will be discussed in a later chapter.

One way to think about an Electrodynamic Tether is that it is a closed electrical circuit with a battery in series. When the tether passes through the ionosphere, it is able to collect electrons, allow them to flow through the conductive wire, and emits them back into the atmosphere. At each end of the EDT will be a plasma contactor, with an anode collecting electrons and a cathode emitting them.

3.3 Limitations

The critical limitations of the EDT are that they are subject to power surges and large vibrations in the tether. Micrometeoroids and space debris present another concern to the EDT, as is the case with the MXT. Micrometeoroids pose the danger of severing the tether, and the only way to counter that eventuality is to have redundant current paths that can make up for single string failure.

A power surge, or electrostatic discharge, through the EDT can occur unexpectedly. This can make a multitude of functions go awry by cutting the tether, damaging its electronics, or welding parts of the machinery together. The only way to surmount this obstacle is to refine the technology to better cope with the dangers posed by the Earth's atmosphere.

EDTs have a tendency to build up vibrations from the variations in the Earth's magnetic field. Unless these vibrations are damped, the tether will eventually fail from mechanical stress. One way to prevent excessive vibrations is to install radio or inertial sensors in the tether, and vary the current in it suitably to damp out the oscillations.[4]

3.4 Applications

There are two primary applications of the EDT. As discussed in the functionality section, the EDT, when equipped with a battery to maintain its orbital altitude, can generate electrical power without falling into lower orbit. This would reduce the need for other sources of power for the attached satellite.

The other use of the EDT is to de-orbit a satellite at the end of its useful life and prevent it from becoming a piece of space debris. At the end of the satellite's life, a long wire antenna, previously installed in the object, could be unfurled. When the antenna is in place, a current could be made to flow through it and the resulting **JXB** drag force on it from the Earth's magnetic field would decrease the satellite's speed and cause it to drop to a lower orbit, eventually causing it to enter the Earth's atmosphere and burn up.[22] This is illustrated in Figure 8.

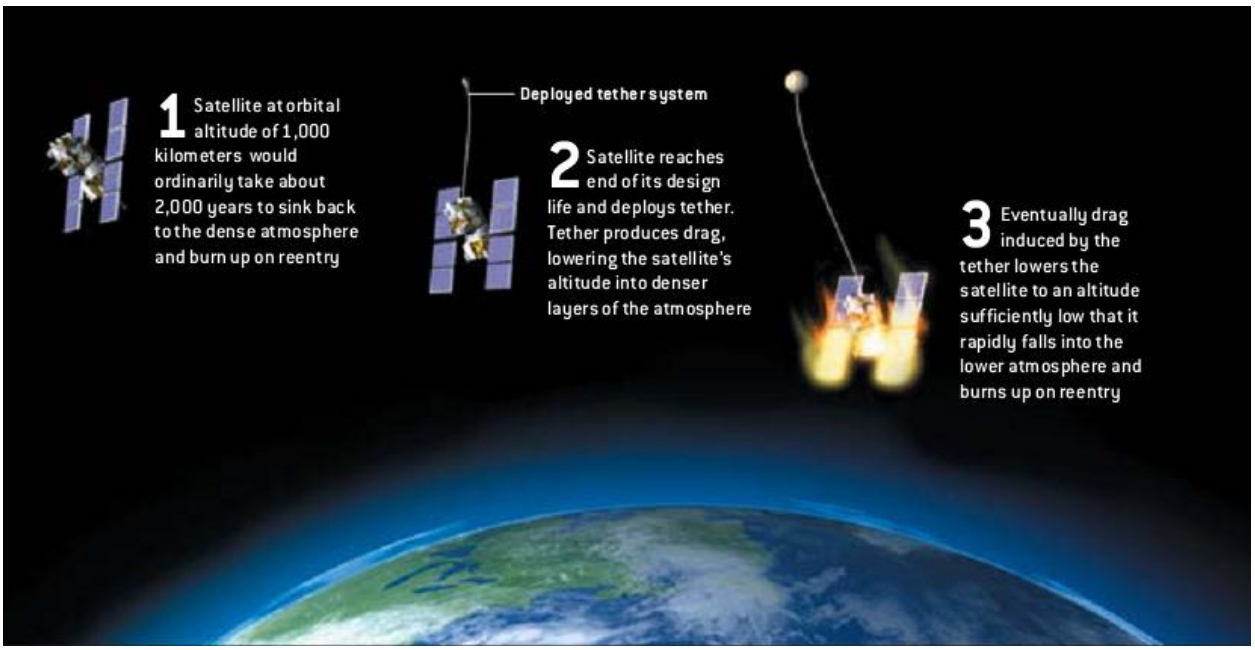

FIGURE 8: EDT APPLICATION TO REMOVE SPACE DEBRIS[1]

A brilliant application of an EDT would be to stabilize the orbit of the International Space Station. The ISS, over the period of the next ten years, will require 70 tons of propellant to keep a non-decaying orbit around the Earth. This propellant's cost is $7,000 USD per pound. With the numbers given, the total amount spent, just to keep the ISS in orbit at its current orbital altitude, comes out to $980,000,000 USD. The idea of an alternative method of keeping the ISS at its orbital altitude becomes a viable option with the EDT. Deployed properly, the EDT could utilize the same electromagnetic forces that held itself in orbit to hold the ISS in orbit, pushing itself forward on the magnetic field of the Earth. This plan would call for no propellant, only an additional power source to ensure the EDT's additional load did not affect its ability to maintain orbital altitude.[22]

The implications this tether could have on missions to other planets, most currently (2007), Mars, would be that the need to carry expendable propellant would be negated. The EDT could be used in a similar manner to boost a spacecraft into a transfer orbit that would take it to a distant planet or destination. Upon reaching its destination, the reverse current could be applied to utilize the resultant drag force to decelerate a spacecraft into the desired final orbit.

4 Momentum Exchange Electrodynamic Reboost Tether

4.1 Functionality

The Momentum-Exchange/Electrodynamic-Reboost Tether utilizes and combines the major functions of the Momentum-Exchange Tether and the Electrodynamic Tether. The MXER's momentum-exchange abilities involve launching a payload from LEO to a higher orbit. Its electrodynamic properties include the ability to raise the tether's orbit after transferring some of its orbital energy to the payload. Combining these two features is the key to creating a successful hybrid that can open up a new approach to space travel.

The momentum-exchange portion of the MXER functions in the same way as was described in Chapter 2.1. The tether will be in an elliptical orbit with a perigee of 300-500 km, and an apogee of 5000-8000 km. The payload will be launched into a circular orbit around the Earth, which has significantly less orbital energy at the same altitude as the tether. The tip of the tether will have a zero relative velocity to the payload when they meet and will be able to safely grasp onto it using a catch mechanism. The example used previously was that the MXER moves at 8.9 km/s, while the payload moves at 7.7 km/s. The tip of the tether, however, is moving at a relative velocity of -1.2 km/s, which makes the difference in velocity zero between the payload and the tip of the tether.[17]

The catch mechanism that will grab onto the payload is a very important part of the entire process. The grapple mechanism must be very strong and have room for error. A connection must be made between the tether grapple and the payload as they come into proximity within about 5-15 seconds.[32] Even though this type of short period capture has not yet been tested in space, there are other systems that have perfected captures of this sort that are used in many applications. Landing jets on an aircraft carrier involves high relative velocities, unpredictable relative accelerations, and small windows of opportunity for a successful capture of the aircraft's hook. Another example is the mid-air capture of film canisters that are dropped by surveillance satellites, which have 2 second rendezvous windows and high relative velocities, yet have a 100% success rate.[32]

Part of the MXER tether will have a conductive wire incorporated into it, which will provide the facility with electrodynamic propulsion by using the Earth's magnetic field. Power will be collected using several solar panels that are stationed periodically on the tether and stored onboard to be used at the appropriate time. This stored energy is used to create a force in the direction of tether movement by inducing a current flow through the conducting wire. The force will be exerted as the tether passes through, and reacts with, the Earth's ionosphere, 150-1000 km above the Earth's surface. After releasing the payload into higher orbit through momentum transfer, the orbit of the tether will be lowered. However, the force created by the reaction between the tether's current and the Earth's magnetic field can be used to reboost its orbit back to its original altitude.

If the MXER tether facility caught and released a 2000 kg payload, the apogee altitude of the tether would decrease by over 2000 km and it would need a Delta-V of about 242 m/s to boost back to its former orbit.[33] It would take about 45 days to complete this process[33], since the EDT can only create thrust near perigee[17] and each individual thrust is very slight. The initial launch of the MXER tether employs the same strategy to initially raise itself to the appropriate altitude. Once the tether facility is launched and the tether is fully extended, it will use the electrodynamic propulsion to raise the apogee altitude to approximately 8200 km, which may take up to 6 months to complete.

The main function of the MXER tether is to capture a payload that will rendezvous with the tether at perigee, throw the payload into a higher orbit, and subsequently reboost itself using electrodynamic propulsion. These steps are summed up in Figure 9:

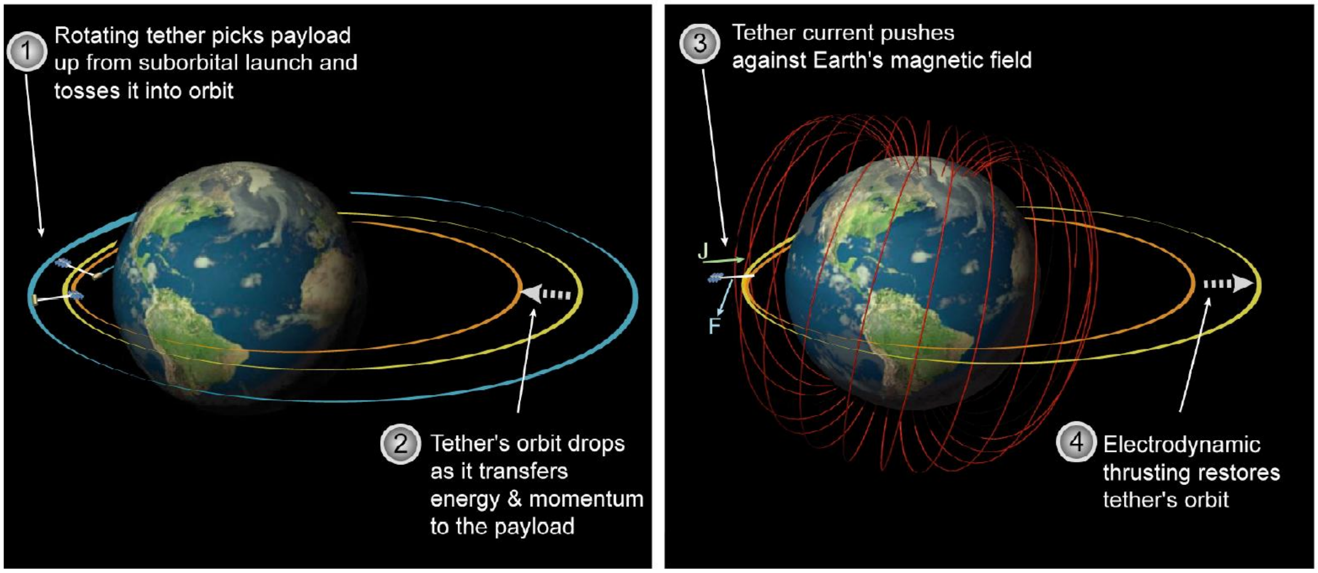

FIGURE 9: STEPS INVOLVED IN MXER PAYLOAD TRANSFER AND REBOOST[33]

In this figure, the yellow line is the MXER's original orbit, the orange line is the MXER's orbit after momentum transfer, the blue line is the payload's new orbit after momentum transfer, and the red lines represent the Earth's magnetic field.

4.2 Construction

Before delving into the construction of the MXER, it is important to take note of prior efforts at MXER architecture. The concept of the MXER originated in the 1990s and has evolved a great deal since. The process of using an electrodynamic reboost system for a propellantless system and related studies were completed by the end of 1992. Agencies such as NASA and Forward Unlimited as well as the Smithsonian Astrophysical Observatory and Boeing were involved in these efforts, the latter investigating the feasibility of a momentum-exchange facility for LEO to GTO payload transfer. The recommendation of all these studies was for a "monolithic" system architecture, in which the tether deploy mechanism, the power systems, and the additional components are integrated into a single control station located at either end of the tether system's center of mass.[33]

The previous "monolithic" system architecture had many limitations that could be overcome only by introducing a new architecture. The new architecture that was proposed[33] is a modular tether boost facility in which the tether consists of a large number of small, identical modules. This is illustrated in Figure 10, below:

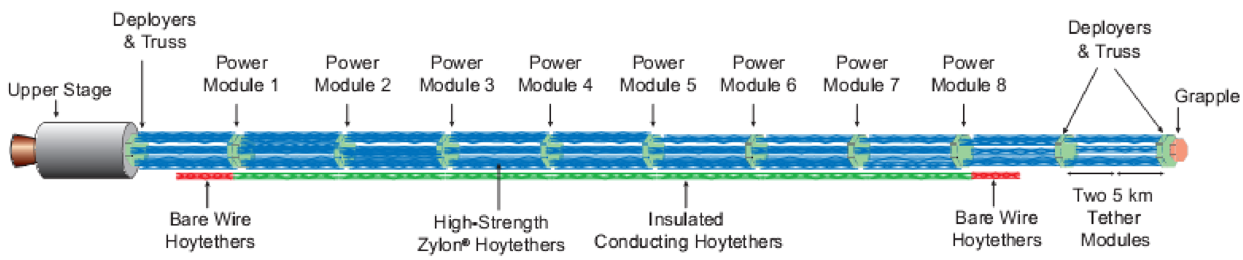

FIGURE 10: CONCEPTUAL LAYOUT OF THE MODULAR MXER TETHER ARCHITECTURE[33]

The five basic building blocks for this new modular architecture are not completely foreign to previous tether designs. As in previous architectures, a high strength tether module is required and, as in the EDT, a conductive Electrodynamic Tether module is required. A deployer reel assembly with ability to deploy and retract both kinds of tether modules is a new addition not present in the MXT or the EDT designs. Finally, there is a power module and a truss structure that supports the deployer module and power module at each junction.[33]

As can be seen in Figure 10, the proposed architecture calls for the 100 km tether structure to be divided into ten sections, each 10 km in length. Further, each 10 km section is composed of several parallel pairs of 5 km tether modules that are attached back-to-back to form the total length. This is illustrated in Figure 10on the right most side. The truss structure serves as a support for each of the tether deployer modules, sitting in between each section of the tether. Eight of the junctions will contain power modules which will supply the high voltage needed for the electrodynamic reboost.[33]

An important feature of the 10 km segments, comprised of two 5 km tethers, is that it affords the tether deployment or retraction mechanism to be placed at both ends of the tether. With this system, in the case that one end become damaged or severed, both halves of the tether can be retracted which will prevent the generation of orbital debris and allow stowing of the broken pieces to facilitate replacement.[33]

While some features of this architecture borrow from other tether constructs such as the MXT and the EDT, the deployer module is relatively new. In this modular architecture, each of the 5 km lengths of high-strength tether and conductive Electrodynamic Tether will be deployed by its own deployer module. A design concept illustration can be found in Figure 11, below:

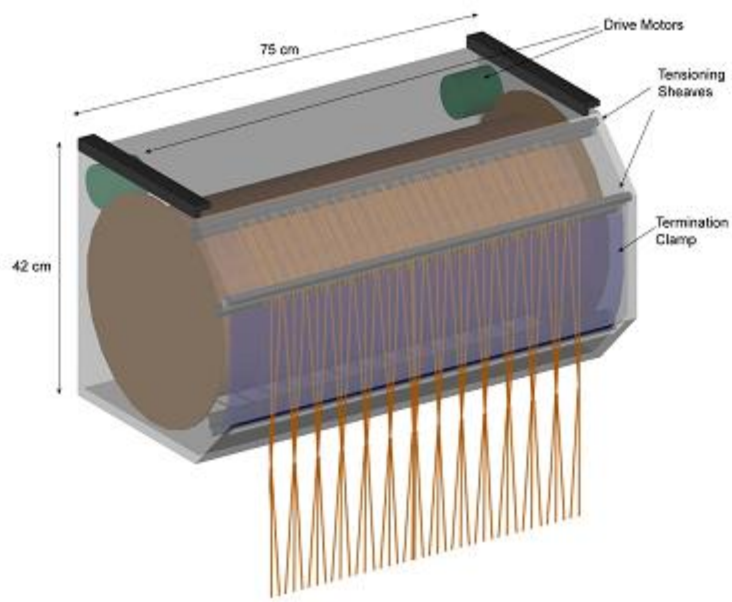

FIGURE 11: CONCEPT DESIGN FOR THE DEPLOYER MODULES[33]

These deployer modules have a design requirement that they must be able to stow 0.1 cubic meters of wound tether for deployment and be able to retract the tethers under low tension, and to securely terminate high-strength tethers prior to the system spin up. Preliminary tests with Zylon Hoytethers, a type of high-strength tether material, show that the tether modules can be wound up with a packing density of 800 kg/m^3, at the least. This means that these spools will be able to easily hold the high-strength tether modules with room left over.[33]

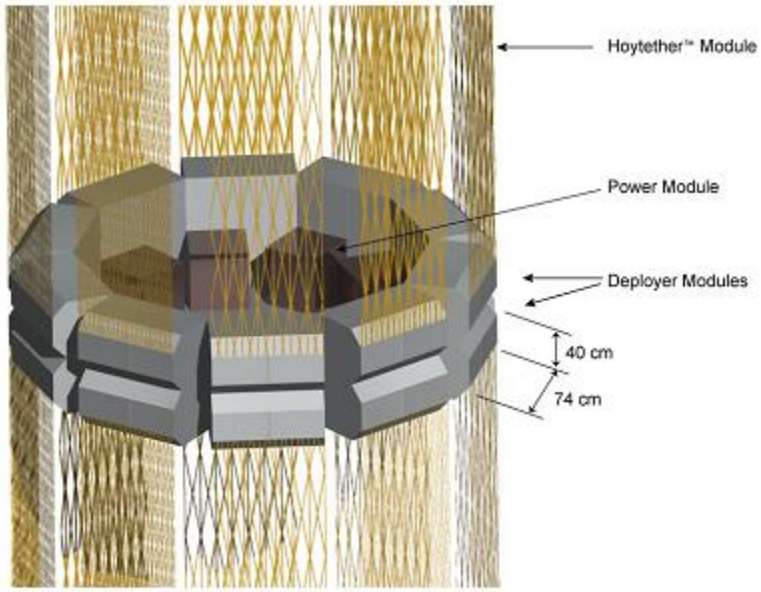

FIGURE 12: CLOSE VIEW OF A POWER/DEPLOYER ASSEMBLY[33]

The truss structure represents another tether concept that plays a vital part in the MXER architecture. The truss structure houses the power module and is the base to which the deployer modules will attach. The truss structure does not require high strength because the loads from the deployers can be transferred directly to one another, given the correct design. The truss structure's primary function is to provide the primary load-bearing path for the launch configuration of the system.[33]

The payload capture mechanism represents another important part of the MXER design. The grappling mechanism has many challenging requirements it must fulfill in order to be deemed usable in Space Tether applications. The payload capture mechanism must be able to secure a 2000 kg payload with short docking time periods as well as low positional error tolerances (± 5 m with respect to all X/Y/Z coordinate planes). The mass of the payload must be supported at up to 6 gees of accelerations which can be further broken down into a 2 gee nominal acceleration due to tether rotation plus 50% due to capture dynamics. These values are then multiplied by the safety factor, 2, to obtain the 6 gees number.[33]

Currently, there is a proof-of-concept demonstration of a payload capture mechanism that is intended for use in the MXER. This system is called the GRASP-MX or, explicitly, the "Grapple, Retrieve, And Secure Payload for Momentum Exchange."[33] The device provides a large volume box-net into which the payload will drift as well as a simple method to close and capture the payload within the box. The next two figures, Figure 13 and Figure 14, show the computer aided design and the proof-of-concept design, respectively:

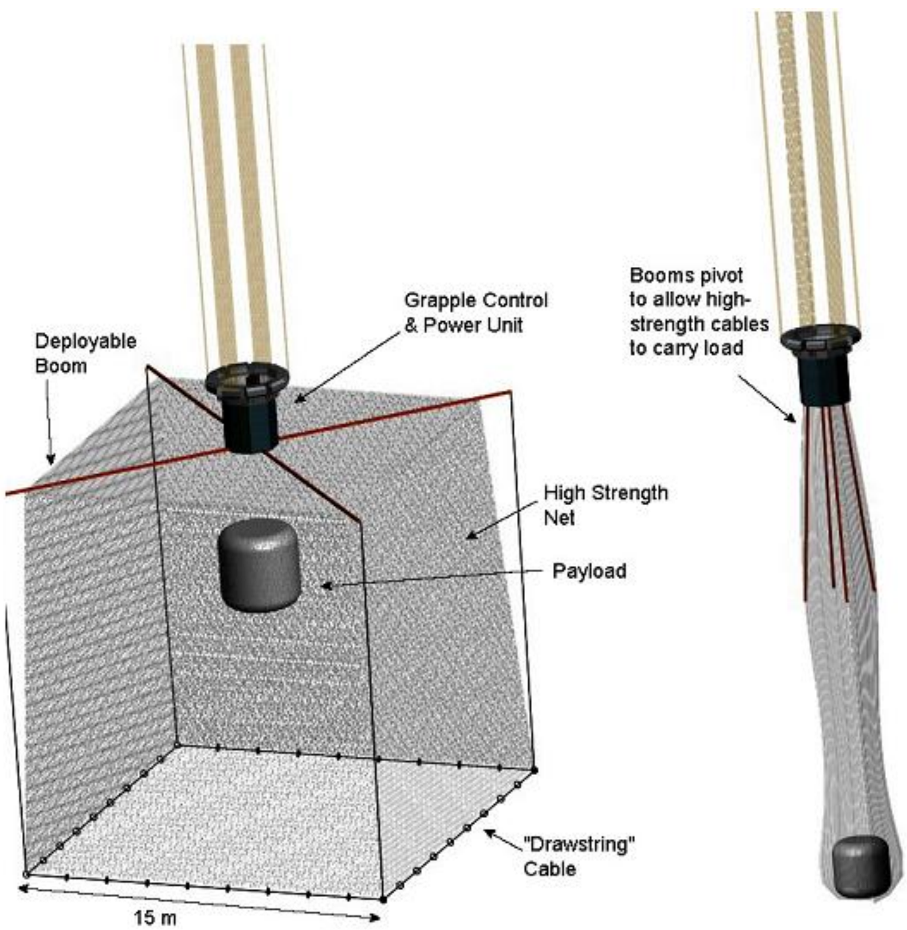

FIGURE 13: CAD CONCEPT DRAWING OF THE GRASP-MX PAYLOAD CAPTURE SYSTEM[33]

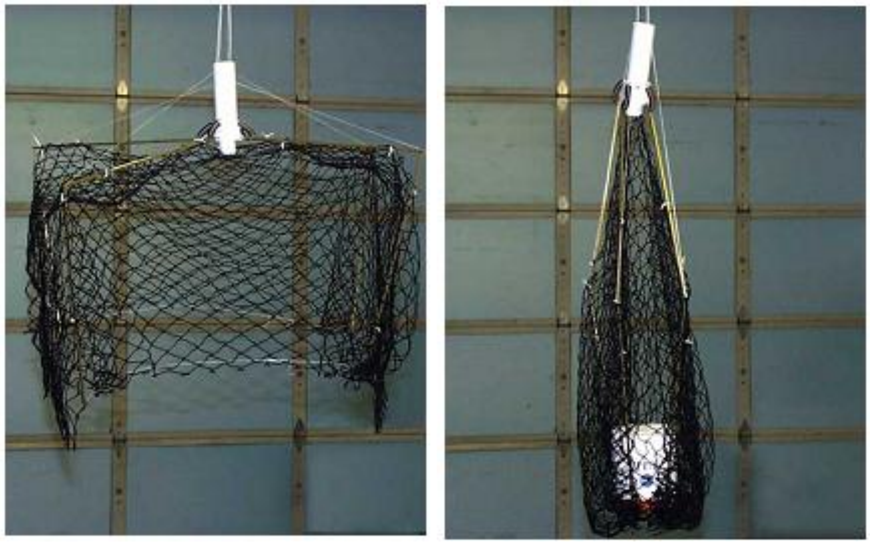

FIGURE 14: PROOF-OF-CONCEPT DEMO OF THE GRASP-MX CONCEPT[33]

This box-net can be 10 m or more on a side and will be opened via spread booms. To achieve capture of a payload, the payload will first be maneuvered to enter the box. The sensors on the GRASP-MX device will detect the payload and automatically activate a mechanism, known as the "drawstring", which will rapidly close the bottom of the box-net. For payload release, the GRASP-MX system will loosen the "drawstring" and allow the payload to simply glide out of the net. If this method is determined to be insufficient, a robotic arm could be outfitted that would slide down the center of the net and assist in payload release.[33]

4.3 LIMITATIONS

While the MXER tether system has the greatest potential for success and multiple uses, the MXER faces some technological challenges that must be overcome before its full potential can be realized. Some of these challenges arise from the applications foreseen for the MXER while others are connected with the construction of the tether and its survival in the hostile environment of space. It should be further noted that the MXER has some of the same limitations (for example, micrometeoroids) that the EDT and MXT configurations face. This section focuses on the problems facing MXER tethers in connection with some of their applications.

The tether needs to be launched in a highly precise orbit so that its tip and the payload can meet at the same point and with the common velocity required for a particular "catch." The tip of the tether would also need to be equipped with a catching mechanism. While this itself is not a problem, the mechanism would be required to have a tolerance for error in position and velocity so that physical contact can be made with the payload, which would then be required to be released a short time later in an easy manner.[17]

While the tether's construction is quite straightforward, the materials used in its construction can make a significant difference to its durability and longevity. The material must be light and strong and be able to sustain tremendous tension forces, and it must also be able to withstand these forces while resisting the degrading effects of the space environment during its lifetime of operation. Furthermore, this material must be able to have small amounts of conductive material in it or bonded with it in order to provide the conductive path for an electrical current, and it must do so with a minimal level of resistance.[17]

Since the tether will require some onboard power systems, of a longer life span than could be provided by a battery, the tether must have the ability to utilize a solar power converter onboard. This solar power source would need to store energy so that the electrical current can be rapidly driven across the induced voltage gradient while the tether passes through the ionosphere. The ionosphere would not only be the receptor of emitted electrons, but would also act a source of electrons that could flow into the tether. The collected electrons could then be used as a power source to provide a force to reboost the tether.[17] Further damage to the tether could be sustained when it passes through the Van Allen radiation belts, which pose a risk to space structures. The solution to this problem can be obtained by using the onboard solar collector as a high voltage source that will remove trapped radiation, in theory. DARPA-funded experiments and simulations have indicated that ten satellites with 20 kW voltage sources may remediate the inner belt of the Van Allen radiation belts to 1% of the current flux in a period of six months.[26]

As with any vehicle planned for use in space, ease of use and versatility both play an important part in design and development. The tether configuration must be easy to construct, package, launch, deploy, and utilize. In this same spirit of simplicity, the tether and its payloads should not require extensive development of new launch vehicles that would place them in orbit. The tether must provide a sufficient payload capacity to entice attractive potential customers who will fund the project, and be able to prove that its performance exceeds the demands placed on it.[17]

With the expensive failures of TSS-I and TSS-I R shuttle missions, the adoption of a MXER tether system may encounter some opposition, but it should be noted that the failures of the earlier missions were attributed more to design processes than to any physics inherent to the tether system. It should also be noted that SEDS-I and SEDS-2 were low-cost success stories that received very little attention and serve to refute the “high risk” reputation of the tether systems.[26]

4.4 Applications

The primary application of the Momentum-Exchange/Electrodynamic-Reboost Tether is to transfer payloads from low Earth orbit into geosynchronous orbit through a high-thrust transfer orbit. There are already ways to do this, but the key feature of the MXER is its (near) zero propellant usage. The ability to reduce the amount of fuel needed to deliver a payload to its destination will enable customers to use much smaller launch vehicles, reducing the total mission cost by 50-85%. The only propellant needed onboard the tether facility is for slight trajectory corrections to make sure the payload rendezvous is perfectly accurate.[32]

A byproduct of the use of the MXER, inherent in the physics of its operation, is that the transfer times for payloads to GEO will be very short, similar to those of a high-thrust maneuver. To achieve short transfer times conventionally, the spacecraft would require a great amount of fuel, therefore increasing the size and cost of the mission immensely. Another way to create a GTO is to use electric propulsion in a low-thrust maneuver. This will decrease the amount of propellant needed, but greatly increases the transfer time. The MXER combines the best features of both types of maneuvers to offer a unique way to reduce both the time and cost of a fast transfer. Shorter transfer times can decrease the amount of time that a commercial satellite company would have to wait for its product to be fully operational, thereby reducing the costs associated with a long wait.[32]

A feature of the MXER that allows it to generate revenue as soon as it is in use is its reusability. The tether facility would be able to transfer a large number of payloads before it needs to be repaired or replaced.[32] The MXER could essentially “pay for itself” after about 10 uses since the mass of the tether facility (~22000 kg) would be around ten times the mass of the payload (up to 2500 kg) and a typical Moon mission requires one-to-one ration of fuel to payload.[7, 33] It should be noted that the MXER is not only capable of sending payloads of up to 2500 kg from LEO to GEO, but can also send payloads of up to 5000 kg from LEO to middle Earth orbit (MEO), which is used by the Global Positioning System (GPS).[32] Also, the modular design of the tether facility enables it to be modified, repaired, or even reconfigured to be able to serve other purposes. Additional modules for repair or expansion of the facility could be carried directly to the tether by payloads sent to it. These modules can add more payload capacity to the tether as well as provide repairs, if necessary. When the MXER facility needs to be retired, this can easily be accomplished by using the EDT to despin the facility, and then reel in the tether, and finally, using electrodynamic drag, lower its orbit and force it to re-enter the Earth’s atmosphere.[33]

Another important advantage of the MXER system that is often overlooked is that the momentum-exchange mechanism can be fully tested in space before it is used for high value payloads. In conventional rocket systems, many components can be tested on the ground or flown in the air to provide the statistics needed to evaluate the mission before it is launched, but there is no way to fully test the spacecraft in space before it is used for a real mission. The same is true for the initial launch of the MXER, although certain aspects of the facility have already been tested in space, such as the EDT portion by the PMG mission, and the deployment of the tether by the SEDS and TSS missions. However, once the MXER tether is in orbit and ready to be used, it is possible to test it with "dummy" payloads, such as water tanks, to be absolutely sure it is ready for higher value or manned payloads.[32]

Although the MXER tether facility is a technology still under development, there are many ideas for future applications. Once a manned presence is established on the Moon, it is possible to create a lunar orbiting tether to go along with the Earth orbiting MXER that would allow the convenient transportation of goods and resources between the two. A similar idea can be implemented for Mars when a manned presence is established. It could also eventually be possible for the MXER tether to provide interplanetary transfers to planets further than Mars.[26]

All of these capabilities and applications are very beneficial to NASA's space missions, as well as commercial missions. The tether system could greatly reduce the costs of many future missions, making it an economical "gateway to space", in much the same way that the opening of the Panama Canal created new opportunities in ocean shipping that had not previously existed. [6]

5 Conclusion

Space tethers come in a variety of types and have numerous applications. Electrodynamic Tethers (EDT) use conducting wires that react with the Earth's magnetic field to either generate power or create a force that can raise or lower a spacecraft's orbit. Momentum-Exchange Tethers (MXT) use the conservation of angular momentum to transfer payloads between orbits. The focus of this project, however, was the Momentum-Exchange/Electrodynamic Reboost tether facility. This concept appeared to be the most promising of the potential applications that space tethers have to offer.

The MXER tether is a hybrid of both an EDT and MXT, combining the architecture and functionality of the two to create an extremely useful facility. It will use momentum-exchange characteristics to catch a payload as it comes into contact with the tether, then transfer the payload from LEO to a higher orbit, and, finally, employ electrodynamic propulsion to reboost its orbit for subsequent missions. This would greatly reduce the overall cost of missions to space since the amount of propellant required by spacecraft to reach higher orbits would be significantly lowered, allowing much smaller spacecraft to be used.

Although the development of the MXER tether is still at a preliminary stage, many individual parts have been tested or are currently being tested in the relevant domain. The feasibility of electrodynamic reboost was tested experimentally in 1993 by the Plasma Motor Generator. The PMG was a 500 m Electrodynamic Tether system which converted orbital energy into electrical energy and successfully raised and lowered its own orbit. The Shuttle-based Tethered Satellite System (TSS-1 and TSS-1R), and the Small Expendable Deployment System (SEDS-I and SEDS-II) missions between 1992 and 1996 showed that long tethers could be deployed by simple mechanisms and operated from a satellite. The Tether Physics and Survivability Experiment (TiPS) mission – a 4 km tether that connected two objects – determined that it was possible for tethers to survive for long periods of time in space, since its launch in 1997. It is currently (2007) still in orbit. The catch mechanism, which is the most difficult part to test, is being developed by the Lockheed Martin Corporation and Tennessee Tech University researchers. They have developed prototypes of grapple mechanisms that could be used on the MXER and have tested them on the ground with conditions that emulate a payload capture.

Despite certain advances in tether-related technology in recent years, the MXER tether still may not become a reality until the distant future. Since the rationale of the MXER is to lower the cost of sending a payload from LEO to GEO, it would need to be reused many times for it to be worth its initial cost. Some of the important technologies of the MXER must be tested in space, which requires flight experiments. Unfortunately, funding support is currently insufficient to make the proper advances that need to be made in order for the potential benefits to be demonstrated in the near future.[17] NASA's In-Space Propulsion Technology Program is providing moderate funding for the research and development of space tethers, but there is no major program established to proffer adequate funding for the technology to be moved into a prototype stage.[17]

The only way to increase the support and enthusiasm for space tethers is to educate both the general public and the engineers and scientists in the aerospace field.[17] If more people realize the potential benefits of tethers in space, then more funding and support will become available. To help raise awareness of tethers and other technologies, future IQP teams may be able to research other tether applications, such as the electrodynamic reboost of the International Space Station. Another option may be to research ways to educate the public and interview those in relevant fields about the potential technological impact of the tethers. Future IQP teams would be able to use this report as a foundation to expand upon, or as a stepping stone that could help orient them in the right direction.

Glossary

Apogee – (aka Apoapsis) the point in an orbit farthest from the body being orbited.

Electromotive Force – The amount of energy gained per unit charge that passes through a device in the opposite direction to the electric field produced by that device. It is measured in volts.

Geostationary Orbit (GEO) – A circular orbit at 35786 km above Earth's surface and in the same plane as the equator. In this configuration, a spacecraft's orbital velocity is matched to the rotational velocity of the planet and the spacecraft appears to hang motionless above one point on the planet's surface.

Geostationary Transfer Orbit (GTO) – An orbit that takes an object from low Earth orbit (LEO) to a geostationary orbit.

GPa – A GigaPascal is a unit of pressure which can be used to express the strength of a material. It is 10^9 N/m^2 or $1.5x10^5$ psi. This means that a 1 inch square cable of a material with a tensile strength of 1 GPa could lift a 150,000 pound load.

Low Earth Orbit (LEO) – A Low Earth Orbit (LEO) is an orbit that usually ranges from 600 to 2000 km in altitude above the surface of the Earth.

Medium Earth Orbit (MEO) – A type of orbit that typically falls in the range of altitudes of 9,000 - 15,000 kilometers (km) above the surface of the Earth.

Micrometeoroid – a small particle of rock in space, usually weighing less than a gram and moving with a high velocity, that poses a threat to satellites and other manmade structures deployed in space.

Orbital Energy – The specific orbital energy, $\boldsymbol{\varepsilon}$, of an orbiting body traveling through space under standard assumptions is the sum of its potential energy ($\boldsymbol{\varepsilon_p}$) and kinetic energy ($\boldsymbol{\varepsilon_k}$) per unit mass.

Perigee – (aka Periapsis) the point in an orbit closest to the body being orbited.

Space Debris – Fragments from space missions and satellites that are in orbit around the earth.

Strain – Strain is the geometrical expression of deformation caused by the action of stress on a physical body.

Stress – Stress is the internal distribution of forces within a body that balance and react to the loads applied to it.

Tensile Strength – The tensile strength of a material is the maximum amount of tensile stress that it can be subjected to before it breaks.

Tensile Stress – Tensile stress (or tension) is the stress state leading to expansion (volume and/or length of a material tends to increase). In the uniaxial manner of tension, tensile stress is induced by pulling forces across a bar, specimen etc. Tensile stress is the opposite of compressive stress.

Tension – Tension is a force on a body directed to produce strain (extension).

APPENDIX I – PREVIOUS TETHER MISSIONS[19]

Mission	Year	Description
Shuttle-based Tethered Satellite System (TSS-1)	1992	550-kg satellite with a 20-km electronically conductive tether; showed that tethers could be launched and operated from the satellite.
Small Expendable Deployment System (SEDS-I)	1993	25-kg mini satellite with a 20 km non-conductive tether; showed that a long tether could be deployed from a light and simple deployment mechanism with re-entry.
Plasma Motor Generator (PMG)	1993	500 m electro-dynamic tether system; successfully converted orbital energy into electrical energy and was able to raise and lower the orbit.
Small Expendable Deployment System (2nd flight) (SEDS-II)	1994	Same equipment as SEDS-I; mission was a success and provided important data on the micrometeoroid risk.
Re-flight of TSS-1 (TSS-1R)	1996	Performed experiments in space and almost completed its deployment of tether.
Tether Physics and Survivability Experiment (TiPS)	1997	4 km tether connecting two objects to test long-term survivability of tethers in space. The TiPS is still in orbit today and is the only tethered system in space.

Appendix II – Table of Orbits[27, 28, 29, 30, 31]

Type of Orbit	Altitude (km)	Occupied By:
Low Earth Orbit (LEO)	200 – 2000	Space Station, Space Shuttle Missions, majority of artificial satellites, majority of space debris.
Medium Earth Orbit (MEO)	2001 – 35785	GPS satellites, Van Allen belt radiation.
Geostationary Orbit (GEO)	35786	Weather satellites, communication satellites.
Geosynchronous Orbit	42164	Satellites, Space Elevators (in theory)
Geostationary Transfer Orbit (GTO)	24582	Connects LEO and GEO. Not permanently occupied.

APPENDIX III – TABLE OF POSSIBLE TETHER MATERIALS AND THEIR PROPERTIES[17]

Material	Tensile Strength (GPa)	Density (kg/m^3)
CNT	300	1300
Steel	1.2	7900
Kevlar	3.6	1440
Spectra 2000 (Dyneema)	3.5	970
Zylon	5.8	1540
Current PIPD	5.3	1700
Anticipated PIPD	9.5	1700

APPENDIX IV – TABLE OF ACRONYMS

Acronym	**Meaning**
CNT	Carbon Nanotube
EDT	Electrodynamic Tether
EMF	Electromotive Force
FRDT	Facilities Requirement Definition Team
GEO	Geosynchronous Orbit
GPa	GigaPascal
GTO	Geostationary Transfer Orbit
ISA	Italian Space Agency
ISS	International Space Station
LEO	Low Earth Orbit
M/OD	Micrometeoroid/Orbit Debris
MEO	Medium Earth Orbit
MXER	Momentum-Exchange Electrodynamic Reboost
MXT	Momentum-Exchange Tether
NRL	Naval Research Laboratory (U.S.)
PMG	Plasma Motor Generator
TiPS	Tether Physics and Survivability Experiment
TSS	Tethered Satellite System
SEDS	Small Expendable Deployment System
NASA	National Aeronautics and Space Administration

APPENDIX V – TABLE OF TECHNOLOGY UNDER DEVELOPMENT[26]

Technology	Organization/Institution
High-Strength, Space-Survivable Tethers	Tethers Unlimited, Inc., Lockheed Martin Corporation
High Fidelity Tether Simulations	Tethers Unlimited, Inc., Tennessee Tech University, Star Technology and Research, Inc.
Capture Mechanisms	Lockheed Martin Corporation, Tennessee Tech University

APPENDIX VI - ORGANIZATIONS DEVELOPING TETHER TECHNOLOGY

Organization/ Institution	Headquarters Location	Website	Description
Tethers Unlimited, Inc. (TUI)	Bothell, WA	http://www.tethers.com/	Tethers Unlimited, Inc. (TUI) is a research and development company specializing in advanced space technologies and scientific computing solutions.
Lockheed Martin Corporation (LHMC)	Bethesda, MD	http://www.lockheedmartin.com/	Lockheed Martin Corporation is an advanced technology company that deals with aeronautics, space systems, and information technology. The majority of Lockheed Martin's business is with U.S. federal government agencies.
Tennessee Tech University (TTU)	Cookeville, TN	http://www.tntech.edu/	Tennessee Tech is a public, co-educational and comprehensive university, which houses strong technical and academic curriculums.
Star Technology and Research, Inc. (STAR, Inc.)	Mount Pleasant, SC	http://www.star-tech-inc.com/	Star Technology and Research, Inc. is a small business that works with government agencies and educational organizations to experiment with and develop mechanical and aerodynamic equipment.

BIBLIOGRAPHY

1. Lorenzini, E., Sanmartin, J. "Electrodynamic Tethers in Space." *Scientific American.* Aug 2004.
2. "The Life of Konstantin Eduardovitch Tsiolkovsky." 10 Oct. 2005. <http://www.informatics.org/museum/>
3. "Arthur C. Clark." 6 Oct 2006. <http://en.wikipedia.org/wiki/Arthur_C_Clark>
4. "Tether Propulsion." 20 Sept 2006. <http://en.wikipedia.org/wiki/Space_tether>
5. "About Space Tethers." *Tethers Unlimited Inc.* <http://www.tethers.com/TethersGeneral.html>
6. "In Space Propulsion: Momentum-Exchange Electrodynamic Reboost (MXER) Tether." *NASA* May 2005 <http://www.nasa.gov/centers/marshall/pdf/115871main_MXER_TS.pdf>
7. Bergin, Chris. "Sling me to the Moon" NASA Space Flight. 18 Jan. 2006 <http://www.nasaspaceflight.com/content/?cid=4202>
8. "Hypersonic Airplane Space Tether Orbital Launch (HASTOL) System." 9 Nov 1999. <http://www.niac.usra.edu/files/library/meetings/fellows/nov99/355Bogar.pdf>
9. "Icarus Satellite Project." 17 Mar 2003. <http://data.engin.umich.edu/Icarus/proseds_ed.html>
10. "Space Tethers at SAO." 15 Aug 2002. <http://cfa-www.harvard.edu/~spgroup>
11. "DSM – Dyneema." 1 Nov 2006. <http://www.dsm.com/en_US/html/hpf/home_dyneema.htm>
12. "Dyneema." 30 Oct 2006. <http://en.wikipedia.org/wiki/Dyneema>
13. "Introduction to Nanomaterials." 26 Oct 2006. <http://www.nanowerk.com/n_nanomaterials_7.html>
14. "The Wondrous World of Carbon Nanotubes." 27 Feb 2003. <http://students.chem.tue.nl/ifp03/Wondrous%20World%20of%20Carbon%20Nanotubes_Final.pdf>
15. "Micrometeoroid." 16 Sept 2006. <http://en.wikipedia.org/wiki/Micrometeoroid>

16. “Faraday’s Law of Induction.” 29 Oct 2006. <http://en.wikipedia.org/wiki/Faraday%27s_law_of_induction>

17. “MXER TAG 2003 Report.” 24 July 2003. <http://www.nasaspaceflight.com/_docs/MXER%20TAG%202003%20Report.pdf>

18. “Carbon Nanotubes.” 21 Jan 2007. <http://en.wikipedia.org/wiki/Carbon_nanotube>

19. “Special Projects – Tethered Flights.” 22 April 1999. <http://www.cfa.harvard.edu/~spgroup/missions.html>

20. “Tethers in Space Handbook.” Dec 1997. <http://www.tethers.com/papers/TethersInSpace.pdf>

21. Larson, Wiley J., and James R. Wertz, eds. Space Mission Analysis and Design. New York: Springer, 2006.

22. Christensen, Bill. “Electrodynamic Tethers: Getting into the Swing.” 09 November 2004. <http://www.space.com/businesstechnology/technology/technovel_tether_041109.html>

23. “Electrodynamic Tethers.” 14 September 2006. <http://www.tethers.com/EDTethers.html>

24. Hoyt, Robert, and Robert Forward. “The Terminator Tether.” 10 January 2000. <http://www.tethers.com/papers/TTReno00.pdf>

25. Fluegel, Kari. “Plasma Motor Generator to Test New Method of Dissipating Energy in Space.” 25 June 1993. <http://www.nasa.gov/centers/johnson/news/releases/1993_1995/93-049.html>

26. Hoyt, Robert. “Space Tethers: Lessons from Developing “Revolutionary” Technologies.” 2004. < http://www.niac.usra.edu/files/library/meetings/annual/oct04/Hoyt_Robert.pdf>

27. “Low Earth Orbit.” 06 February 2007. <http://en.wikipedia.org/wiki/Low-earth_orbit>

28. “Geosynchronous Orbit.” 07 January 2007. <http://en.wikipedia.org/wiki/Geosynchronous_orbit>

29. “Geostationary transfer orbit.” 21 October 2006. <http://en.wikipedia.org/wiki/Geostationary_transfer_orbit>

30. “Medium Earth Orbit.” 30 January 2007. <http://en.wikipedia.org/wiki/Medium_earth_orbit>

31. “Geostationary orbit.” 01 February 2007. <http://en.wikipedia.org/wiki/Geostationary_orbit>

32. Hoyt, Robert. “Commercial Development of a Tether Transport System.” 17 July 2000. <http://www.tethers.com/papers/JPC00MMOSTT.pdf>

33. Hoyt, R., Slostad, J., Frank, S.. “A Modular Momentum-Exchange/Electrodynamic-Reboost Tether System Architecture.” 2003. < http://www.tethers.com/papers/MXERJPC2003Paper.pdf>