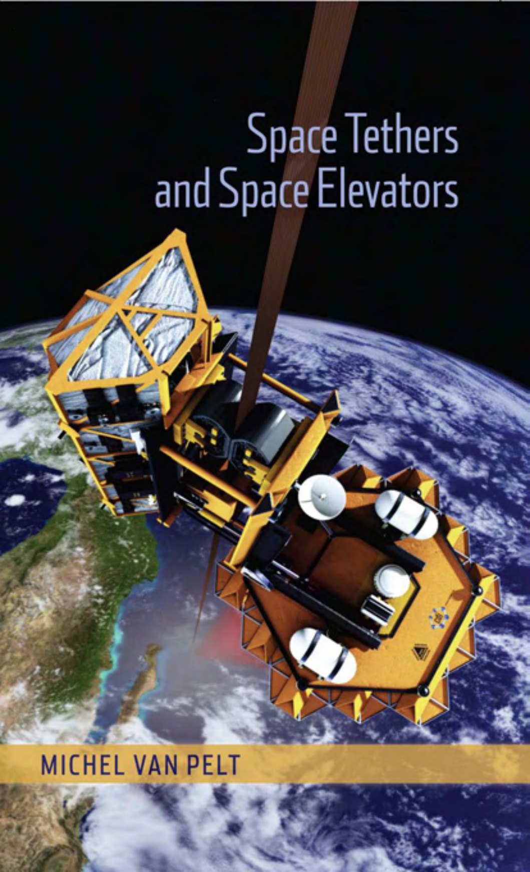
Space Tethers and Space Elevators

MICHEL VAN PELT



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COPERNICUS BOOKS
An Imprint of Springer Science+Business Media

in Association with
Praxis Publishing, Ltd.

Published in the United States by Copernicus Books,
an imprint of Springer Science+Business Media.

Copernicus Books
Springer Science+Business Media
233 Spring Street
New York, NY 10013
www.springer.com

Library of Congress Control Number:
2009926314

Manufactured in the United States of America.
Printed on acid-free paper.

ISBN 978-0-387-76555-6 e-ISBN 978-0-387-76556-3

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To Lucas and Thijs,
who may ride a space elevator one day.

Preface

Space tethers. Unlike space rockets and space probes, it is not a topic many people are familiar with. You may wonder what tethers have to do with space, or what they would be doing there. You may also wonder why it would be interesting to read a book about them.

On Earth, tethers, otherwise known as ropes or lines, are used primarily to bind things together and for climbing and pulling things up. Rock climbers and bungee jumpers use tethers, most elevators are based on them, and even people walking their dog can be considered users of terrestrial tether applications. In space, tethers have similar uses. For instance, they can be used to connect spacecraft to other satellites, space stations, or even asteroids. An advanced tether system, called a "space elevator," may even link Earth's surface directly to orbit, so you could climb all the way into space.

Space tethers also could be used to swing spacecraft from one orbit to another, or even from planet to planet, without using rocket propellant. Tarzan, the fictional jungle king of Edgar Rice Burroughs made famous in numerous movies, used a similar form of tether transportation, swinging from tree to tree on jungle liana vines. Although he is not a rocket scientist, Tarzan has to keep in mind various things that are also critical for designers of space tether systems. For instance, good judgment of the strength of tethers is vital; a breaking vine would seriously ruin Tarzan's day. Moreover, our jungle hero needs to select vines of the right length to reach the place he wants to go. With a too short liana, he will not get to his destination at all; if the vine is too long, he will land too low and maybe even hit the ground. Then there is always the danger of crashing headlong into a tree, so good planning of direction and speed is vital.

Tarzan swings and grabs one vine after another to get through the jungle. That means he needs to know when to let go in order to reach the next vine, and also make sure there is actually another good one to grab at the end of his trajectory—all in all, a fairly complex task, especially for someone educated by apes. Renting a jeep or a boat may be a better idea.

In space, however, tethers have many potential advantages. You can use them to get to the Moon and Mars or de-orbit spacecraft back to Earth without any rocket propulsion. You can drag them through Earth's magnetic field to generate an electrodynamic braking force, and at the same time produce electrical energy for the spacecraft. You can connect several spacecraft with tethers to accurately position them for formation flying. You can create artificial gravity inside a spacecraft by swinging it around at the end of a long tether. And think how much easier it would be to be able to put satellites on a space elevator and simply release them from the top floor, rather than launching them with expensive, noisy, non-reusable, propellant-gulping rockets.

Sounds like science fiction? As you read on, you may be amazed to learn about the number of actual space tether projects that have already flown. These range from small suborbital rocket experiments to large and complicated systems flown onboard the Space Shuttle. The first experiment flew as long ago as 1966, onboard the crewed Gemini 11 mission! Up until now, all tether space missions have been experimental, but in this book you will see what they may lead to. There is a wide array of ideas for small-scale as well as large-scale concepts that have the potential to revolutionize spaceflight in the coming decades.

This book first discusses the basic concepts regarding the use of space tethers, and the physics underlying their functioning. Next, we discuss where the ideas for space tethers came from and what missions with relatively simple tethers have already flown. The chapters after that describe more futuristic possibilities, using tethers to transport spacecraft from Earth into space, operate them in Earth orbit, and even make interplanetary missions more economical. Last, we discuss the main challenges that face the most exiting and potentially most useful applications of large space tethers.

Many thanks to Clive Horwood and John Mason of Praxis, who suggested that I write a book about this fascinating topic. John Mason's comments and inspiring suggestions were of great importance. Stella Tkatchova once again did an excellent job reading the text from a nonengineering perspective, and Alessandro Atzei helped tremendously by reading from an engineering point of view. My space-qualified friends Torsten Bieler, Peter Buist, Dennis Gerrits, Zeina Mounzer, Ron Noteborn, Rogier Schonenborg, and Arno Wielders provided ideas, useful comments and psychological support. Special thanks to the guys from Delta-Utec, Erik van der Heide and Michiel Kruijff, for up-to-date information on their YES missions and a critical look at what I wrote about tether deployment and dynamics. And last but certainly not least, thanks to my wife, Stefania, for all her support, comments, suggestions, and patience.

The Basics

1

The basic concept behind space tethers is not very complicated. Simply put, space tethers are long cables that connect spacecraft to other spacecraft or to objects such as spent rocket stages, asteroids, or even the planet Earth. When two things are connected by a tether, manipulating one object will influence the other; if we pull on one end of the cable, the spacecraft on the other end will also move. By connecting two spacecraft with a tether, we can force them to stay together and orbit Earth as one single system.

Even though objects in orbit are flying around in microgravity conditions, spacecraft in different orbits will turn around a planet or the Sun at different speeds. If we connect two such satellites with a tether, they will each try to go their own way and pull on the cable. The forces on such a tether in space can be very powerful; therefore, space tethers are usually made of thin strands of high-strength fibers. If electricity has to flow through them, conducting wires are also incorporated.

There are many types and applications of tether systems; as we will see, the possibilities for this novel technology are amazing. In this chapter the main types of space tethers are introduced, as a basis for the more detailed descriptions of concepts and missions in later chapters. However, as most tether applications have something to do with satellite orbits, we first need to understand how orbital mechanics work.

Orbits

Imagine throwing a ball horizontally. You will not be surprised by the fact that it follows a curved trajectory and hits the ground some distance away. You will also not be amazed that when you throw the ball a bit faster, it will land farther away. Because its initial horizontal speed is higher, while it is falling and accelerating toward Earth at the same rate as before, the ball will fly a longer distance before hitting the ground. Its trajectory is curved,

M. van Pelt, *Space Tethers and Space Elevators*, DOI: 10.1007/978-0-387-76556-3_1,

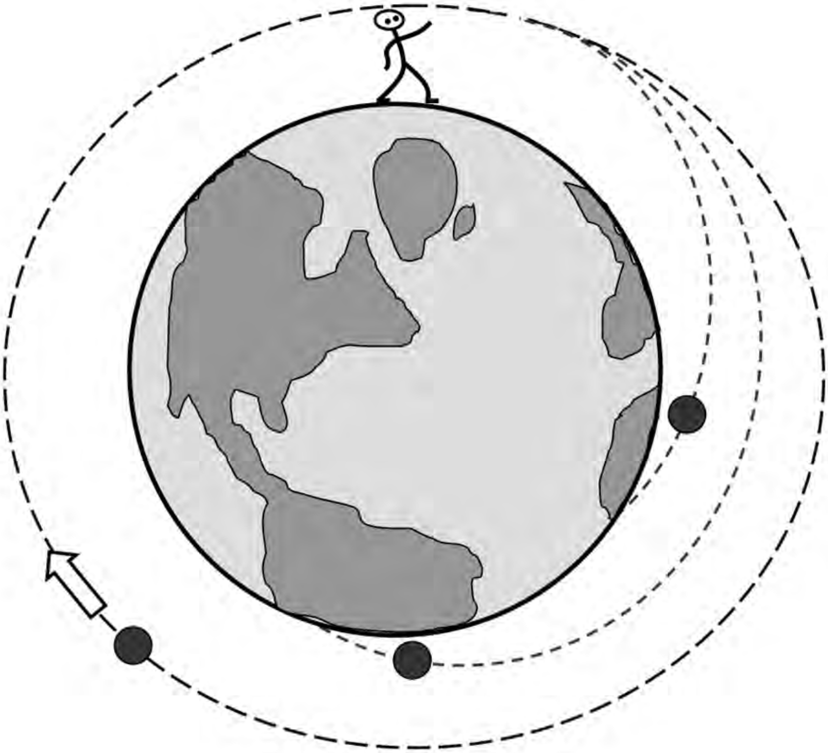

Figure 1.1: The faster an object, the further it travels before hitting the ground. At the right speed it will never hit the ground and thus enter an orbit around Earth.

because of the combination of its horizontal velocity and gravity pulling and thus accelerating the ball downward.

Imagine throwing, or rather shooting, the ball really fast. Now it goes very far, all the way over the horizon. Because Earth is round, its surface drops away under the ball. The result is that the ball will fly farther away than if we lived on a flat world. At a velocity of about 8 kilometer per second (5 miles per second), the curvature of the ball's trajectory under the pull of Earth's gravity is exactly the same as the curvature of Earth. In effect, the ball is continuously falling around the world, never hitting the ground (Fig. 1.1). It is in orbit, and will return to hit you in the back!

In reality you would not be in any danger, because Earth's atmosphere would slow the ball down so much that it would never reach you again. However, at an altitude of over 100 km (60 miles), there is hardly any atmosphere left to decelerate a moving object. In the vacuum of space the ball can circle Earth unhindered and become a satellite.

Now imagine you are standing on top of a tower 200 km (120 miles) high.

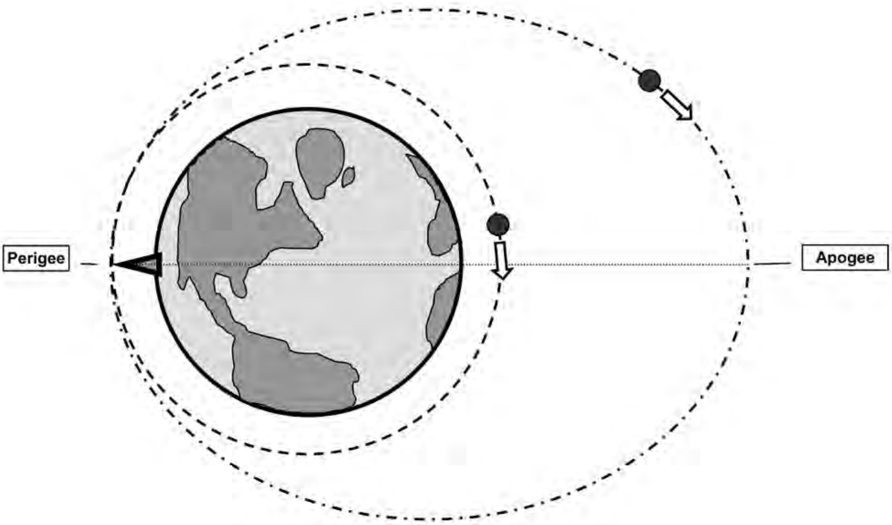

Figure 1.2: If a satellite is launched from a certain altitude with velocity higher than necessary for a circular orbit, it will enter an elliptical orbit.

If you shoot the ball at exactly the right speed, it will get into a circular orbit exactly 200 km above Earth's surface. What happens if you shoot it away at a higher velocity? Then the satellite has too much energy and flies too far to perfectly match the curvature of Earth. It will nevertheless still return to its point of origin (the top of the tower); instead of a perfect circle, the ball's orbit is now a large ellipse. In this elliptical orbit, the top of the tower is the point closest to the Earth. This is called the orbit's "perigee" (Fig. 1.2).

If you accidentally shoot the ball at a slightly too low velocity, the result would also be an elliptical orbit. However, now the trajectory is initially too curved to be a perfect circle, and the ball will drop down to an altitude of less than 200 km before returning to its point of origin. In this case the top of the tower is the orbit's furthest point from Earth, what is called the "apogee." If the velocity is much too low, the orbit intersects Earth's atmosphere. If that happens, the air drag will slow down the satellite even further and make it de-orbit.

Perigee and *apogee* are terms used for Earth orbits. The generic terms are *periapsis* and *apoapsis,* but the prefixes *peri-* and *ap-* or *apo-* are commonly applied to the Greek or Roman names of the planets being orbited: *perigee* and *apogee* for Earth, *perijove* and *apojove* for Jupiter, *periselene* and *aposelene* for the Moon, and *perihelion* and *aphelion* for satellites, planets, and other objects orbiting the sun.

Satellite orbits are normally changed with the help of rocket propulsion. Speeding up a satellite in a circular orbit by thrusting in the direction of its velocity will make it enter a larger, elliptical orbit; the perigee stays the same, but the extra speed increases the orbit's apogee. You can also make the satellite follow a smaller elliptical orbit by thrusting in the other direction, in effect putting the brakes on. Now the apogee stays what it was (the altitude of the original circular orbit), but the perigee is much closer to Earth.

Getting a satellite from a low circular orbit into a higher circular orbit normally involves two steps. First, the orbit's apogee is increased by accelerating the satellite with a rocket engine. The engine has to work only for a limited amount of time, until the right speed is achieved. Once the satellite has entered its new, elliptical orbit, it simply cruises unpowered over half an ellipse to its now higher apogee. This is called a Hohmann trajectory, and it is the most energy-efficient way for getting a satellite from a lower orbit to a higher one. Once it arrives there, the engine is ignited a second time. If the velocity is increased by exactly the right amount, the orbit becomes circular again. If the increase is too high, the satellite enters

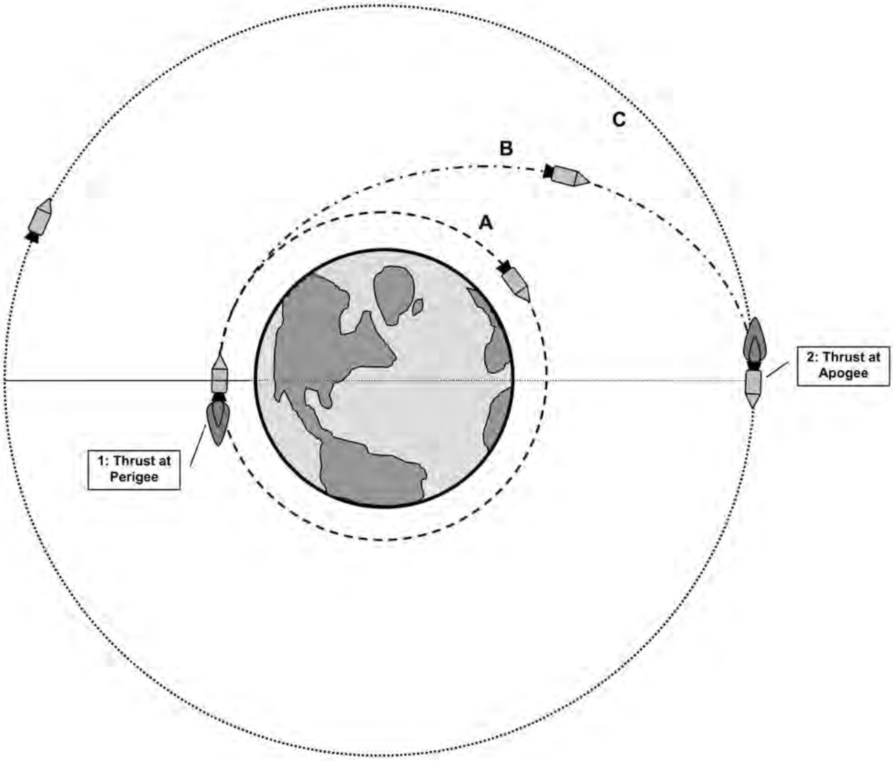

Figure 1.3: A thrust impulse in circular orbit A sends a rocket into the elliptical orbit B. A second thrust impulse half an orbit later (at the new apogee) will then send it into orbit C, which is also circular but much higher than orbit A.

another, larger elliptical orbit, with the previous apogee becoming the new perigee. After each kick from the rocket's engine, the old and the new orbit thus always have one point in common: the place where the rocket was ignited (Fig. 1.3).

Another important thing to know about orbits is that the higher the orbit, the lower the velocity required for a satellite to stay in that orbit. This sounds a bit contradictory, because didn't we need to speed up a satellite to move it from a low Earth orbit into a higher one? Yes, but the initial kick given to a spacecraft to increase its orbit's apogee only gives it a higher velocity at its initial altitude. As the satellite cruises along its new, elliptical orbit to a higher altitude, its velocity steadily decreases due to the gravity of Earth. Once it reaches its apogee, the spacecraft actually flies too slow to stay there; that's why it falls back to its perigee, which is at the same altitude as its original, pre-kick orbit (the common point of both orbits, where the rocket engine was originally fired). Falling down, it picks up speed due to the pull of gravity, and at its lowest altitude will move too fast to stay in a circular orbit there (in fact, at perigee it will move at the exact same speed it left with after the initial propulsive boost we gave it). It therefore moves back up to higher altitude again. If nothing else happens, the satellite will thus stay in this stable, elliptical orbit, constantly decreasing its speed on the way up, and increasing velocity on the way down (Fig. 1.4).

Now, at the elliptical orbit's apogee, we again need to give our satellite a little extra kick to increase its speed sufficiently to make it stay at that altitude, in a nice circular orbit. Nevertheless, its velocity in this stable, higher circular orbit will be lower than its orbital velocity in the original, lower circular orbit. The extra energy we gave it with the first kick has been spent on gaining altitude, not on a higher velocity at that altitude (remember, the satellite actually moves relatively slow at apogee).

If the force of Earth's gravity would be the same at any altitude, we would expect to require a higher horizontal velocity for higher orbits; a higher orbit means a bigger circle around Earth, which means a less curved trajectory, which in turn means a higher horizontal velocity. It would be similar to the example of throwing a ball: the higher the horizontal speed, the less curved the trajectory and the wider the orbit, and thus the farther away the ball flies.

However, a planet's gravity is not constant at all, but instead weakens with distance. The farther away (in effect the higher the altitude), the lower the strength of Earth's gravity. If you weigh 70 kilograms (kg) (150 pounds) at Earth's surface, you will weigh 41 kg (90 pounds) at an altitude of 2000 km, and only 2 kg (4 pounds) at 36,000 km (22,000 miles) above Earth. The higher the orbit, the weaker the pull of gravity, and as a result the lower the velocity required for a ball or satellite to stay in orbit and not fall back down

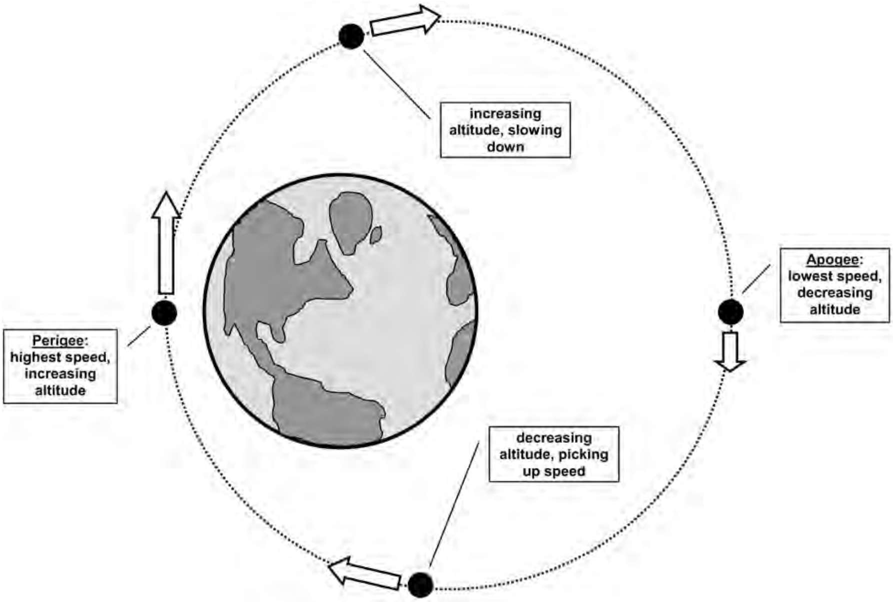

Figure 1.4: A satellite has its highest velocity at perigee and its lowest velocity at apogee.

to Earth. In other words, because its rate of fall toward the planet is less due to the lower gravity, a satellite's horizontal velocity can be lower while its trajectory will still be sufficiently curved to avoid hitting the ground. The effect of gravity decreasing with altitude wins over the earlier explained effect of requiring a higher orbital velocity for a larger orbit. The net result is thus that the higher the orbit, the slower the satellite.

To stay in a circular orbit at an altitude of 150 km (90 miles) requires an object to move at a velocity of 7.8 km per second (4.8 miles per second). At an altitude of 2000 km (1200 miles), this has decreased to 6.9 km per second (4.3 miles per second), and at 36,000 km (22,000 miles) the orbital velocity is only 3.1 km per second (1.9 miles per second). This velocity in combination with the size of the orbit means that at an altitude of 36,000 km (22,000 miles), a satellite will make one complete orbit in exactly 24 hours. Because Earth also rotates once in 24 hours, a satellite at that altitude and orbiting above the equator will appear to hang over the same spot on Earth continuously. This is called the geostationary Earth orbit. If a spacecraft orbits at the same altitude but not exactly above the equator, it will seem to remain motionless above the same longitude but periodically move north and south. Such orbits are called geosynchronous orbits (GEOs); a geostationary orbit is thus a special type of GEO. Even farther out, the Moon orbits at an altitude of about 384,000 km (240,000 miles) and a

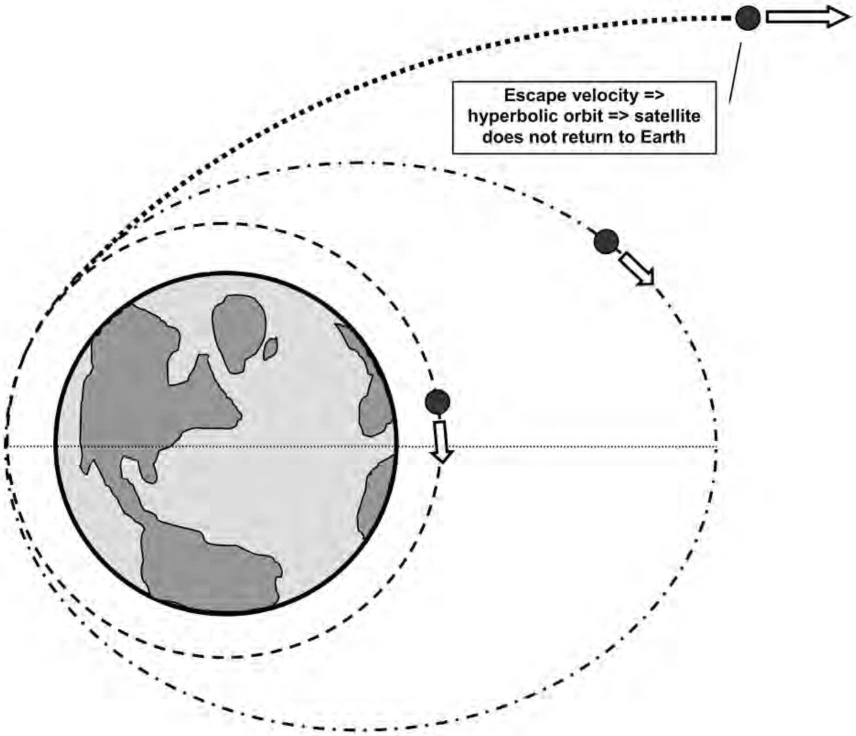

Figure 1.5: A satellite that achieves a speed equal to or greater than Earth's escape velocity does not return to Earth but enters a new orbit around the Sun.

velocity of only 1 km per second (0.6 miles per second). Because of its low speed and its very large orbit, it takes the Moon over 27 days to circle around Earth once.

Since the strength of gravity diminishes with altitude (called the gravity gradient), and we can get to a higher altitude by increasing orbital velocity (increasing the orbit's apoapsis), there must be a speed that makes a satellite fly so far away from a planet that it no longer returns. This is called the escape velocity. Below the escape velocity a satellite will follow a circular or elliptical, and thus closed, orbit. Above this speed limit the orbit is an open hyperbola and the spacecraft will "escape" the gravitational influence of the planet (Fig. 1.5).

For Earth, the escape velocity from the surface is about 11 km/s (7 miles/s). Because gravity weakens with altitude, the escape velocity, for example, at an altitude of 5000 km (3100 miles) in space is less: 8.4 km/s (5.2 miles/s). To fly a spacecraft to other planets, it needs to go faster than the local escape velocity. Away from Earth, the gravitational influence of the Sun will become dominant, and the spacecraft will enter an orbit around the Sun. In such an orbit it may fly from one planet to another. For example, with the right increase in velocity a solar orbit that starts in the vicinity of Earth (the perihelion) can reach all the way to the orbit of Mars (the orbit's aphelion). Using such an Earth–Mars Hohmann trajectory, we can efficiently send an interplanetary spacecraft to the red planet. However, we will have to boost the satellite out of Earth orbit at exactly the right time, so that when it arrives in the orbit of Mars that planet will actually be there, at the same location.

Of course, the Sun has its own escape velocity. When this is exceeded, a spacecraft leaves the solar system and enters interstellar space. It will still be in orbit around a dominant center of gravity, though—the heart of the Milky Way, our own galaxy.

Changing orbits by thrusting with rocket engines is expensive in terms of mass. For instance, bringing a 1500-kg (3300-pound) satellite from a low, 150-km (90-mile) altitude orbit to GEO with the efficient method described before takes about 4000 kg (8800 pounds) of propellant (using a typical spacecraft propulsion system burning monomethyl hydrazine and nitrogen tetroxide). This means that the total mass the launcher has to initially put in low Earth orbit is about 3.7 times the mass of the actual GEO satellite! Moreover, the propellant required for the transfer needs to be packaged into tanks that have a considerable mass as well, and also the mass of the essential pipes, filters, valves, structures, and rocket thrusters diminish the "useful" satellite mass delivered in GEO.

The GEO is a popular location, because seen from Earth a satellite in this orbit appears to hang more or less stationary in the sky (it will move north and south a bit, if not orbiting precisely above the equator). Such a satellite can thus be used to permanently observe the same half of Earth, or act as a giant radio/television tower. With three satellites, we can in principle cover the whole planet (with two satellites we would not be able to properly monitor the edges of the half globe observed by each spacecraft; some overlap is needed). Many weather and communications satellites are therefore placed in GEO. There are now about 350 active satellites in that orbit (theoretically three giant satellites would be enough, but those would be impossible to launch, and furthermore there are many different types of satellites and applications, operated by many different countries, organizations and companies) (Fig. 1.6).

If we would somehow be able to transfer a satellite from a low orbit into GEO without rocket propulsion, we would save a large amount of mass on propellant and onboard propulsion equipment. This would then enable us to use a smaller and therefore cheaper launcher. Launching a 1500-kg (3300-pound) spacecraft into a low orbit can be done, for example, with a Russian

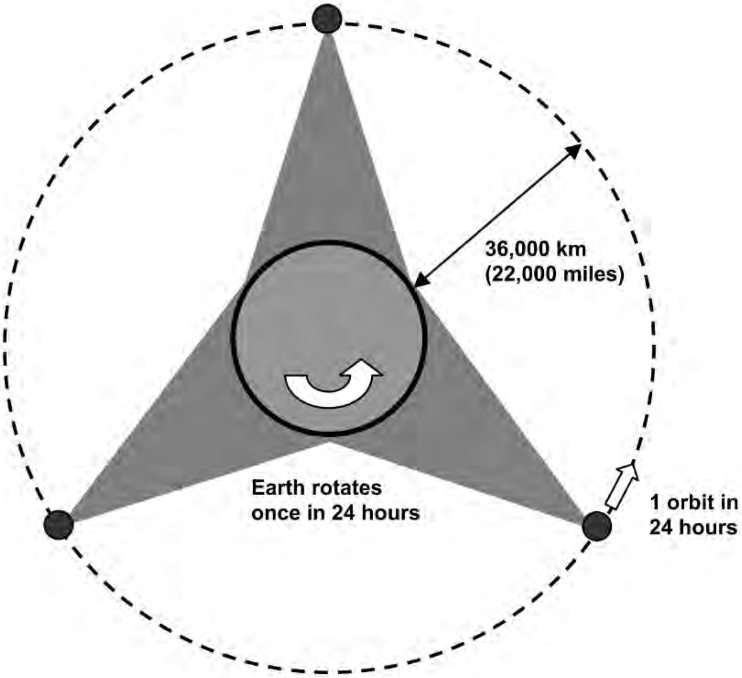

Figure 1.6: With three satellites in a geosynchronous orbit (GEO), practically the entire globe can be covered.

Eurockot launcher, which costs about $15 million. To launch the same satellite plus the added mass for propellant and equipment needed for the transfer to GEO takes something like a Russian Soyuz rocket, with a launch price of some $45 million—three times the price of the smaller rocket. As we will see later on, the smart use of space tethers (using so-called tether propulsion systems) makes it possible to transfer satellites into the desired orbit with no or relatively little amounts of propellant, potentially resulting in important launch cost savings.

Formation Flying

Probably the most obvious application of tethers is to use them to connect satellites and thus keep them together. In orbit, spacecraft that are initially close together tend to slowly drift away from each other. This may be because they were put in orbit with slightly different initial velocities, or because they are orbiting at somewhat different altitudes. Moreover, Earth is not perfectly round, and as a result its gravity field is not exactly the same everywhere at a given altitude. Satellites at different locations thus experience slightly different disturbances in the gravity field and eventually start to move in different directions.

Propulsion with small rocket thrusters can be used to push back satellites that drift away from their positions, but that requires propellant. Eventually the propellant runs out and then there will be no way to keep the spacecraft under control. Moreover, to keep track of the spacecraft's position with respect to other spacecraft, we will need to equip each satellite with accurate position measurement sensors. The necessary propulsion and sensor equipment adds complexity and risk, and increases the mass and cost of the satellites. In addition, there are formation-flying applications for which even the smallest amount of thrust can be too disturbing.

Using tethers, we can build up a constellation of physically interconnected satellites that act as a single, much larger spacecraft, without the need for propulsion and complicated sensors to keep the cluster together. For example, a large radio astronomy antenna dish, requiring a very large spacecraft, could be replaced by a series of smaller antennas on smaller spacecraft. For these small antennas to work together and function as a single large dish, they have to remain very accurately positioned with respect to each other. The simplest method to keep them together is to connect them with cables and thus force them to stay in a tight formation, like flies caught in a spider's web.

However, since the cables need to be long and yet light, because otherwise it becomes too expensive to launch them and too difficult to roll them up to fit in the launcher, they will need to be very flexible. That means we can pull on the tethers, but the moment we push them the cables will go slack and we lose control of our herd of spacecraft. In other words, tethers can be used to prevent satellites from flying away, but we need something else to keep them from moving toward each other. Rocket thrusters can be used for that, but they would have to work continuously and thus use up a lot of propellant, which is what we tried to avoid by using tethers in the first place.

A better idea is to make the constellation spin around its own center of mass. This results in a centrifugal force that tries to make the satellites fly outward, and in reaction a centripetal, pulling force on the tethers (physics purists say that the centripetal force is only an apparent force, not a real force, but we can ignore the mathematical niceties here). The pull will keep the tethers taut, ensuring that the satellites all stay together. Imagine spinning around fast while in each hand holding a rope with a weight attached. As an interconnected constellation, the three of you will keep your relative positions with respect to each other. The "push" that prevents the weights from crashing into you is provided by the centrifugal forces caused

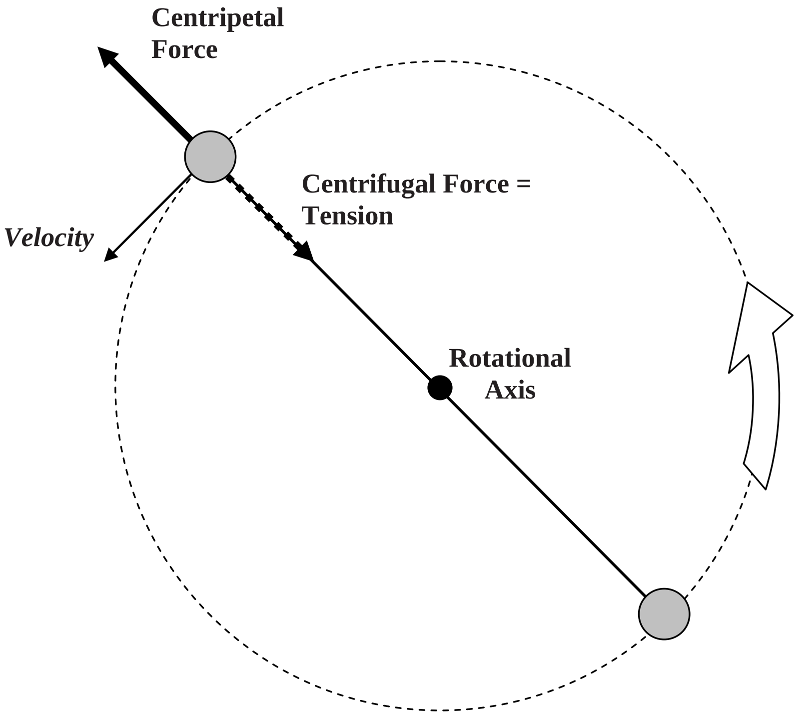

Figure 1.7: Centrifugal and centripetal forces in a rotating constellation with two masses or satellites.

by the rapid rotation, while the taut ropes prevent them from shooting away due to equal but inward directed centripetal tension forces (Fig. 1.7).

The downside of this method is that the group of satellites needs to rotate; their relative positions may remain fixed, but to the rest of the universe the satellites are constantly moving. This is not practical for many formation-flying applications, such as observing a planet or a star. There are, however, other ways to push spacecraft away from each other that do not use propellant and that can be combined with tether interconnections. This will be explained later (see Let's Stay Together, in Chapter 5).

Safety Tethers

If tethers can be employed to keep satellites together, it is not a far stretch to imagine their use in securing astronauts to prevent them from drifting away. In the 1960s the first spacewalkers used tethers that not only secured them to

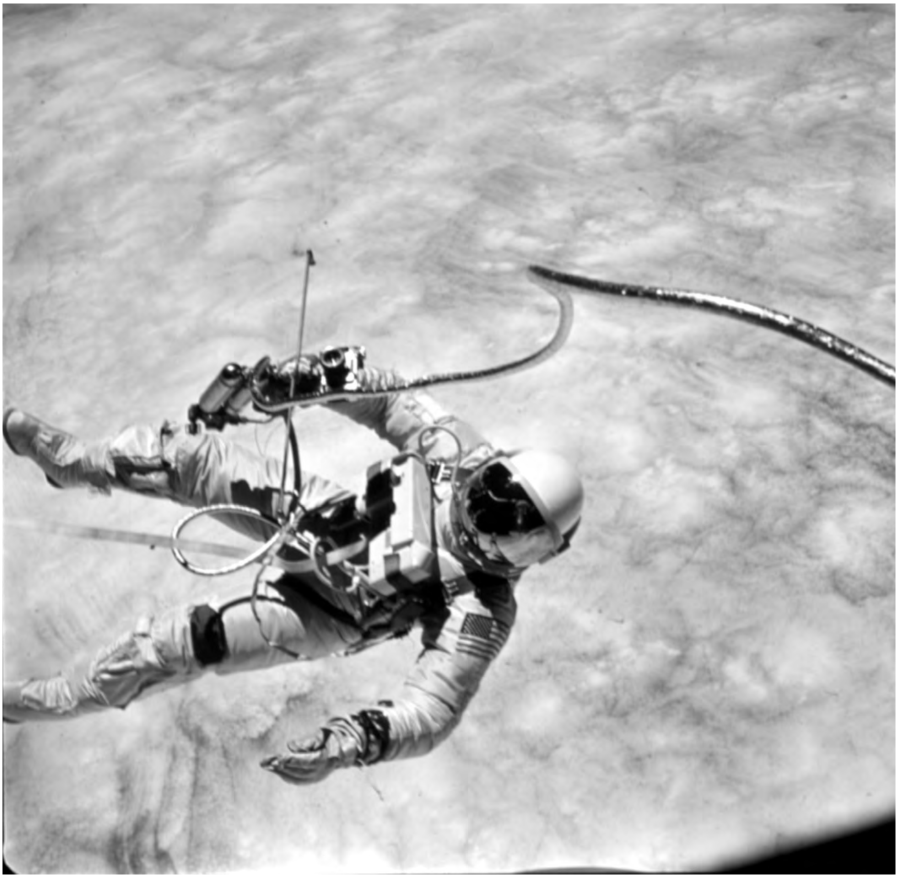

Figure 1.8: Astronaut Ed White during his space walk in 1965. He was connected to the Gemini 4 spacecraft by a long tether. (Courtesy of the National Aeronautics and Space Administration [NASA].)

their spacecraft but also contained wires and hoses for electrical, communication, and life support systems. At the end of a spacewalk, astronauts pulled themselves along the tether back to their capsules. Nowadays, spacesuits have their own, completely independent systems included in an attached backpack, but cables are still used as safety lines that connect astronauts to their spacecraft or space station (Fig. 1.8).

The tethers used for this function are relatively short, on the order of several meters. However, researchers at the Massachusetts Institute of Technology (MIT; Cambridge, MA) have devised an application with long tethers that can help astronauts strolling across the surface of small asteroids without floating away. Asteroids have very little gravity, so walking on them is much more difficult than walking on a planet. An asteroid with a diameter of less than 8 km (5 miles) would have so little mass and therefore gravity that an astronaut could easily fly off into space when making a small jump or even a step.

Tying a lightweight rope all the way around an asteroid could be a solution; astronauts could attach themselves to this safety line and maneuver or even walk along the surface. The MIT researchers envision that their system will be deployed by an astronaut or spacecraft unwinding a spool of rope while flying around the asteroid. The rope might cut into the soft, granular surface of an asteroid, but even then it could at least give spacewalkers something to hold onto.

Artificial Gravity

Microgravity, or weightlessness, exists inside an orbiting spacecraft because its contents (including any astronauts) are falling around Earth—we call this "free fall"—at the same speed as the spacecraft itself (and not, as is often believed, because there is no gravity in space). It is like being inside a falling elevator, but without the hard landing at the end. Astronauts inside the International Space Station (ISS) can simply float through its many modules, have dinner on a wall, and sleep on the ceiling. Because of the microgravity, there is no gravity-defined up or down.

This is fun for the astronauts, but the main use for space stations is that the microgravity conditions allow many kinds of experiments that are not possible on Earth. It is like turning off gravity. Fluids that float one on top of another on Earth can suddenly be mixed, as there is no gravity-induced separation based on differences in density. Larger and purer crystals can be grown, and the importance of gravity for the growth of cells and microbes can be studied.

We can even do combustion experiments that are not possible on the ground. A candle burning in space does not show the familiar elongated shape of the flame, but instead is spherical and almost transparent blue. The spherical shape is caused by the lack of convection, that is, heated air moving up, because that depends on gravity. There is no "up" for the hot air to go to, so it just stays hanging around the flame. The combustion in the hot bubble is very efficient because partly burned particles are not rapidly transported away by rising hot gases, but instead remain near the heat so they can burn up completely. Microgravity allows us to study combustion processes in great detail, which teaches us how to optimize combustion, for example, in car engines on Earth, and thereby reduce pollution.

However, if we want to fly people to Mars, microgravity is not so great.

Astronauts' bodies get upset by the lack of gravity. Blood normally pulled down into the legs now tends to move upward to the head, muscles are used much less and therefore deteriorate, and the body notices it do not need to maintain a strong skeleton anymore so it allows bones to weaken (leading to a loss of bone mass). Even though astronauts onboard the ISS typically exercise 2 hours a day to mitigate muscle atrophy, their strength inevitably weakens, especially in the legs. After half a year on the station, it may take an astronaut months to gain back his normal strength. As a result, healthy space explorers who land on Mars after a flight of half a year may not even be able to walk anymore, despite the much lower gravity on the red planet.

The centrifugal force that can be used to keep tethered satellite clusters together can also be employed to generate artificial gravity. Fill a bucket with water and swirl it around at the end of a length of rope. If you do it fast enough, the water will not spill out. It is as if the liquid is pulled toward the now vertical bottom of the bucket. Another analogy is riding through a loop in a roller coaster without falling out. Even while upside down you are being pushed into your seat by the artificial gravity generated by the train's velocity in combination with the curved track.

In a similar way, putting crewed modules at the end of long beams and having the spacecraft rotate can generate artificial gravity for astronauts. That enables them to live more normally and prevents them from being affected by the harmful physiological changes resulting from exposure to microgravity. In principle, we can attach such modules to each other with heavy structures and thus create a spinning wheel, with people living on the inner rim. This is the idea behind classical designs for wheel-shaped space stations such as seen in the movie *2001: A Space Odyssey* and in many conceptual studies for space colonies (Fig. 1.9).

The level of artificial gravity in such a system is determined by the length of the beams between the modules, the spacecraft center of rotation (i.e., the center of mass), and the rotational speed. The gravity level can be raised by lengthening the beams as well as by increasing the rotational speed. We can easily check this out with the earlier described bucket of water on a rope. The artificial gravity increases linearly with the length of the beam/rope and with the square of the number of rotations per minute. Thus, a double beam length (i.e., radius) gives a doubling of the "gravity" level if the number of rotations per minute is kept the same, but doubling the rotational speed increases it by four.

In theory, a gravity similar to that on Earth can be achieved with a spacecraft with short beams that rotates very fast, for example using a radius of 4 meters (13 feet) and 15 rotations per minute. However, if you have ever sat on a fast merry-go-round and moved your head, you know that fast

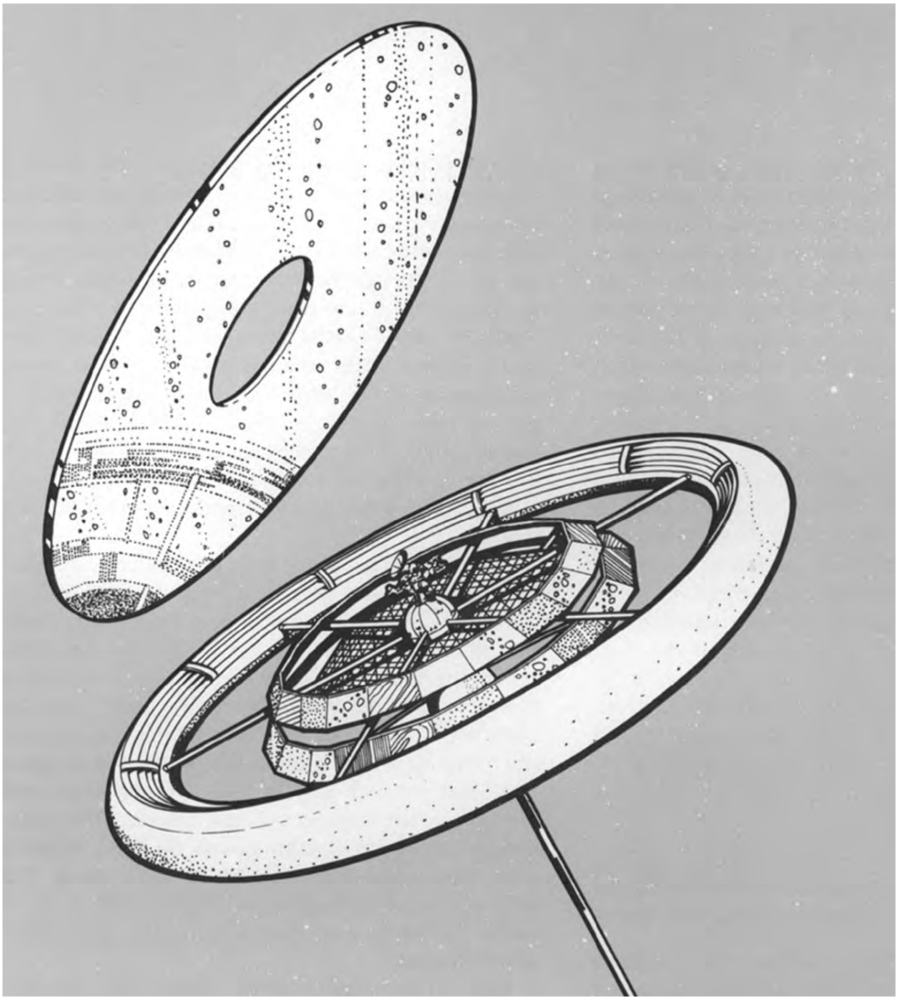

Figure 1.9: A concept for a wheel-shaped space colony with artificial gravity. There is a large mirror orbiting above the wheel to reflect sunlight into the colony. (Courtesy of NASA.)

rotations can be very uncomfortable. Anything moving in a rotating system experiences sudden accelerations in directions perpendicular to the axis of rotation. In other words, when you move your head away from or toward the center of a merry-go-round, you will feel as if you are speeding up or slowing down. The result is motion sickness. People can adapt to a maximum of six rotations per minute, but the number of rotations for comfortable living seems to be about two.

To create sufficient levels of artificial gravity without making the

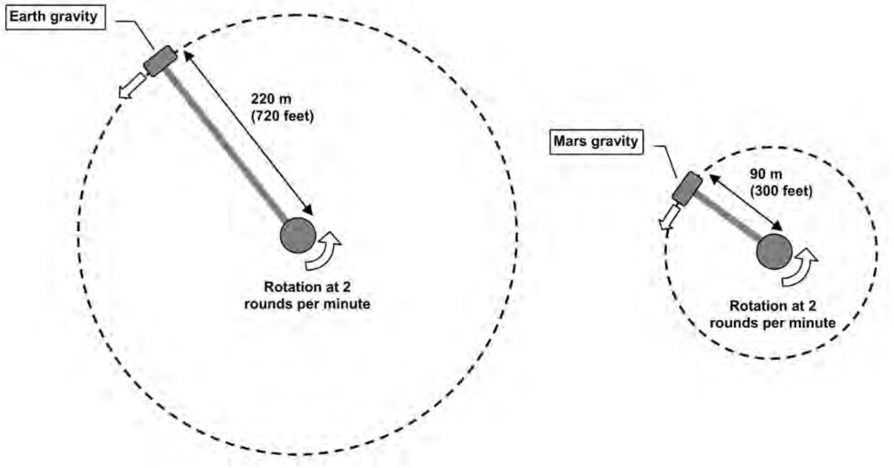

Figure 1.10: The generation of gravity similar to that on the surface of Earth or Mars requires a large radius in order to limit the rotation rate.

spacecraft spin so fast that everybody gets sick requires beams that are several hundred meters long. Earth surface gravity simulation at two rotations per minute means a radius of 220 meters (720 feet), that is, a combined beam length or rotational diameter of 440 meters (1440 feet). Mars surface gravity is 62 percent lower, but at two rotations per minute still requires beams that are 90 meters (300 feet) long (Fig. 1.10).

That means fairly heavy beams. Furthermore, because such long structures do not fit into a rocket, they would need to be launched in pieces and assembled in space. However, since these beams experience only tension forces, they could be replaced by tethers. These are much lighter and thinner, and can be rolled up for launch so that no assembly in orbit is required. On a mission to Mars, the astronauts can deploy the system once they have entered the right transfer orbit, and wind up the tether when arriving at Mars to simplify both spacecraft maneuvering and the astronauts' moving from the habitation modules to the rest of the ship.

Probe Towing

Earth satellites generally orbit well above an altitude of 200 km (120 miles), because below that height the atmosphere is so dense that aerodynamic drag quickly slows a spacecraft, making it fall back to Earth. Gas-filled balloons, on the other hand, can reach altitudes up to about 50 km (30 miles) and stay there for days, but can go no higher. The zone in the middle, between 50 and

100 km, can be reached by sounding rockets that zoom up and then fall back down. However, these rockets stay in the upper atmosphere for only a couple of minutes. At the moment there are no possibilities to reach the upper atmosphere and conduct experiments there for extended periods.

A large satellite in a sufficiently high and thus virtually drag-free orbit could be used to tow a smaller probe on a long tether through the upper layers of the atmosphere. The aerodynamic drag on the probe and tether would start to slow down the mother satellite, but the higher its mass, the more difficult it is to decelerate. A rocket engine can be used to temporarily compensate for the drag, and once the scientific measurements of the atmosphere are done, the tether can be cut so that the large satellite can remain in orbit.

This concept can in principle be applied at all planets with an atmosphere: Earth, Venus, Mars, and the giant outer planets Jupiter, Saturn, Uranus, and Neptune. Small tethered probes could be lowered into an alien atmosphere to take gas samples or even to collect Mars dust that is blown up to high altitudes by the wind.

Comet and Asteroid Sample Return

Many comets and asteroids are so small and have so little gravity that it is possible for a spacecraft to hover over their surface, rather than orbit around them at high speed. Such a spacecraft could shoot a tethered penetrator into the body's surface to collect a material sample, which could then be reeled in for onboard experiments or even for return to Earth. Using several of these harpoon-like penetrators, samples could be collected from various places on the same body, or from more than one individual comet or asteroid.

The penetrators could be launched by a spring system at a distance of several tens of meters from the surface, and then ignite simple solid propellant rockets to accelerate themselves to the impact point. A rotating turret housing multiple penetrators would allow the use of a single tether reel system. A major benefit over the use of a lander is the simplicity of the system: there is no need for an automated and careful, soft landing. In case of a problem, the tether could be cut at the spacecraft's end. A disadvantage is the high-shock impact, which makes it necessary to use only very robust scientific experiments and equipment.

A detailed analysis and design for a tethered penetrator system was performed by the Italian aerospace company Alenia for the European Space Agency's Rosetta spacecraft, which is currently on its way to rendezvous with the comet 67P/Churyumov-Gerasimenko in 2014. However, the tether harpoon concept was discarded in favor of a sophisticated, small lander able to make detailed in-situ analysis of the surface composition.

Aerobraking

A satellite with an atmospheric tether attached will slow down due to aerodynamic drag. For atmosphere probing this is a disadvantage, but it can be used to make an orbiting satellite return to Earth. A spacecraft could deploy a tether into the atmosphere so that the drag on the combination, however small, would eventually decelerate the satellite sufficiently for it to fall back to Earth. This can be used for capsules with microgravity experiments onboard that need to be examined in a laboratory on Earth, or to remove obsolete satellites from orbit (in which case the intense heat that is generated when the spacecraft slams into the atmosphere is simply allowed to burn it up). Spacecraft currently returned to Earth without tethers need rocket propulsion systems and considerable amounts of propellant.

Instead of decelerating a spacecraft so that it completely falls out of orbit, tethers can also be used to slow it down only a little bit. Space probes flying to other planets using efficient (Hohmann) transfer orbits arrive at their destination with too much speed. Without slowing down, they would fly past instead of entering orbit around a planet. However, decelerating with rocket thrust uses a lot of propellant and thus adds considerable mass to a space probe (early interplanetary probes such as Pioneer 10 and 11 and the two Voyagers were not equipped with sufficient propellant to slow down, and thus visited their targets for only brief periods during fast flybys).

Close to the target planet, an interplanetary spacecraft could roll out a long tether into the upper atmosphere. This would decelerate the spacecraft to a speed lower than the local escape velocity, so that it would no longer have the energy to fly away from the planet. Once the right velocity has been reached, the tether could be cut and the spacecraft would remain in orbit—all without using any propellant.

Artificial Gravity Assist

Interplanetary space probes often take advantage of the gravity pull of planets and large moons to alter course and gain speed. For these so-called gravity assist maneuvers, a spacecraft flies by a planet and uses its gravitational field and the planet's orbital velocity around the Sun to pick up speed and change direction. It can be somewhat compared to a Ping-Pong ball hitting a revolving fan; the ball will bounce back at a much higher speed and in a different direction from which it was hit into the fan. The maneuver can also work the other way around: if a spacecraft flies by against the direction in which the planet moves around the Sun, the spacecraft will slow down.

There are many more asteroids than planets and moons, but they are all fairly small, and hence their gravity fields are too weak for gravity-assist maneuvers. However, instead of gravity a long tether may be used in an asteroid slingshot flyby. Imagine an interplanetary spacecraft on its way to Jupiter approaching an asteroid, somewhere beyond the orbit of Mars. When it gets relatively close, it fires a tethered harpoon into the space rock—kind of like how the comic-book figure Spiderman slings around the corners of New York skyscrapers. The spacecraft will whirl in an arc around the asteroid. At the right moment the tether is severed and the probe flies off in a different direction and with a different speed due to the asteroid's orbital velocity (the asteroid has dragged the spacecraft on for a little while) (Fig. 1.11).

The force on the spacecraft is determined by the square of its flyby velocity divided by the length of the tether (this is mathematically equivalent to the earlier described artificial gravity being a function of the length of the tether times the square of the rotational speed, because the rotational speed is equivalent to the tip velocity divided by the tether length). If the probe has

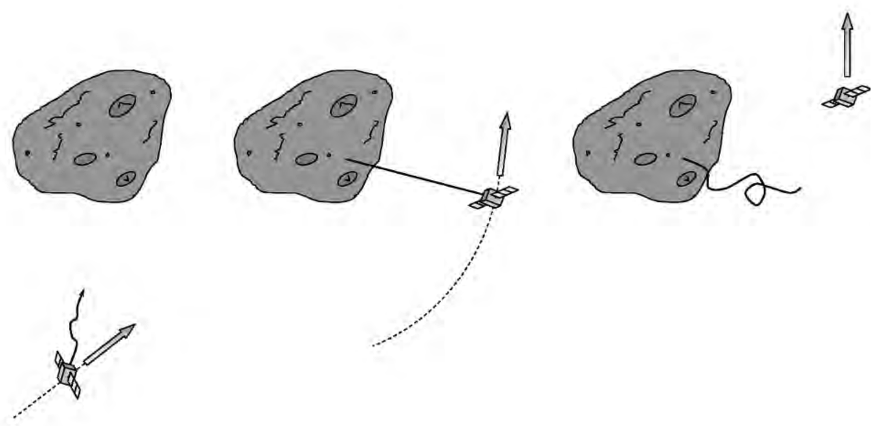

Figure 1.11: The three phases of an artificial gravity assist asteroid flyby maneuver: 1, firing of a tethered harpoon; 2, slingshot around the asteroid; 3, tether release and spacecraft heading off on a different course.

an initial speed of a modest 2 km/s (1.2 miles/s) and the force on the tether and spacecraft needs to be limited to ten times the gravity on the Earth's surface (called 10*g*), the tether has to have a length of at least 40 km (25 miles). Shooting a harpoon from a fast-flying space probe into an asteroid over a distance of tens of kilometers is extremely difficult, and the risk that the harpoon would slip out of the ground during the slingshot maneuver would be very high. The idea is therefore interesting, but probably not very practical.

Momentum Exchange

The most often described space tethers are the momentum exchange tethers, so called because they allow the transfer of momentum (and thus energy) between two objects. The main benefit of these types of tethers is that they allow changing the orbits of spacecraft without using any rocket propulsion.

For example, imagine two equal satellites connected by a long tether and circling Earth, one in a lower orbit than the other. Because the satellites are the same, the center of mass of the combination lies halfway between them. If we want to calculate the orbital speed of this satellite system, we could pretend we are dealing with a single spacecraft located at the combination's center of mass. For the laws of orbital mechanics, it is irrelevant what the satellite system looks like; the whole contraption will stay in orbit as long as its center of mass has the right speed for the altitude at which it is circling.

However, because the lower satellite is closer to Earth than is the center of mass, it is actually orbiting too slowly for its altitude. It will therefore try to fall back to Earth. In contrast, the other satellite is moving too fast for the gravity at its orbital altitude, and will try to pull away. Because the spacecraft are kept together by the tether, they continue orbiting at an average speed that is too high for the lower satellite and too slow for the higher one, but just right for the system as a whole—that is, its center of mass. The result is that both satellites are pulling like dogs on a leash, so that the tether remains taut and forces the two to orbit like a single spacecraft system. Moreover, because one satellite is trying to fall back to Earth and the other is trying to pull away, the tether system automatically orientates itself into a stable, vertical position perpendicular to Earth's surface.

Since this effect is caused by the difference in gravity at different orbital altitudes, it is called gravity-gradient stabilization. It is as if the lower satellite is being dragged along by the higher one, and in turn the upper satellite is pulled back by the lower satellite. The spacecraft are basically sharing their individual momentum via the tether, hence the term *momentum exchange* *tether.* If the tether would go slack, each satellite would be able to move independently and go its own way, one moving down and one up until the tether was stretched tight and vertical again.

What happens if we cut the tether? The lower, "too slow" satellite is now free to follow its own orbit and starts to fall. Because it lacks the energy to stay at its original altitude, it will enter an elliptical orbit with a lower perigee than before. Its original orbital altitude becomes its apogee. If the new orbit intersects Earth's atmosphere, that is, if the perigee is too low, the lower satellite will actually reenter the atmosphere. Momentum exchange tethers can thus be used to return cargo capsules back to Earth or make obsolete satellites leave orbit and burn up in the atmosphere.

The upper, "too fast" satellite, on the other hand, will shoot away to a higher altitude because it has too much energy. Its elliptical orbit will have its perigee at the altitude of the satellites original, forced orbit, but a higher apogee than before. The two spacecraft have been put into different orbits using "tether propulsion" rather than rocket propulsion (Fig. 1.12).

The process is analogous to what happens when an Olympic hammer thrower spins around and then lets go of the heavy weight. The hammer will fly away, while in reaction the athlete is forced to step back (we can think

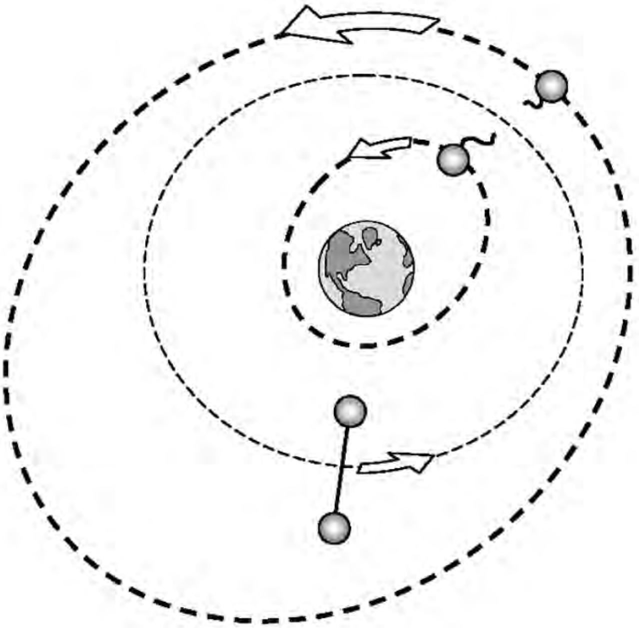

Figure 1.12: Two satellites connected by a tether will each enter a new orbit when the tether is cut, one going down, the other going up.

of the hammer as the higher altitude satellite and the thrower as the lower altitude spacecraft).

An interesting consequence of the dynamics of momentum exchange tethers is that in this case it is possible to "push" on a cable! On Earth, cables can be used only to pull things with, because they go slack the moment you release the tension on them. However, if we push the lower satellite in our example, for example using a rocket motor, it goes into a higher orbit. As a consequence, the upper satellite is given some leeway and allowed to increase its altitude as well, until blocked once more by the pull of the tether. As a result, the whole combination (i.e., the center of mass) will now enter a higher orbit; effectively we have pushed the satellites up, as if they were connected by a steel rod rather than a thin, flexible tether.

Cable Catapults

The Cable Catapult System is an idea of the late Robert L. Forward (he died in September 2002) of Tethers Unlimited, a company working on the development of advanced space tether concepts. Forward was also a famous science-fiction writer who featured space tethers in many of his books; the cable catapult appears in his novel *Camelot 30K* (1993), but it is more than just fantasy.

The Cable Catapult System uses a long tether as a launch rail in combination with a so-called linear motor. A linear motor is a type of electric motor that makes use of electromagnetic forces without requiring any moving parts. On Earth, linear motors are for instance used in magnetic levitation (maglev) trains. The tether, which may be orbiting Earth or another planet, is extended in space and pointed in the right direction for the launch. The linear motor, with the to-be-launched spacecraft attached, then "climbs" forward along the tether and accelerates. Because of the lack of moving parts and because it is electromagnetically suspended and thus does not actually touch the tether, the linear motor and its cargo can reach very high speeds. When the required velocity has been reached, the payload is released to fly to its destination. The motor is subsequently decelerated on a shorter section of the tether, so that the whole launch system can be used again (its orbit will have changed, however, because as the payload accelerates and flies off it pushes the tether backward, following Newton's famous principle of action equals reaction). According to Tethers Unlimited, launch velocities of up to 100 km/s (60 miles/s) may be possible, which would enable interplanetary transfer flights with durations of months rather than years (Fig. 1.13).

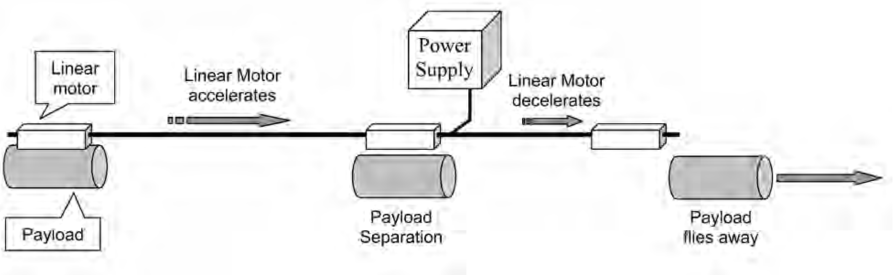

Figure 1.13: The principle of the Cable Catapult System.

In Forward's novel, scientists launch themselves to the outer solar system using a cable catapult to investigate an alien civilization found there. The power supply for the catapult is a nuclear-thermal-electric system (using the heat of a nuclear reactor to produce electrical power). The energy is used to generate a sustained burst of radiofrequency energy, which travels down the long conductive cable to be absorbed by the launching motor. This linear motor then uses a magnetic coupling to pull on the conducting cable and accelerate ("like a monkey climbing a rope," as Forward writes in the book). Just before the motor reaches the power supply, which is located at an optimum point along the cable, it releases the payload capsule. Then it slows down to a stop on the shorter length of the cable, on the other side of the power supply. Using a fixed power supply rather than one on the linear motor minimizes the mass that needs to be accelerated, and therefore the amount of energy required. Due to the electric resistance of the cable, part of the energy flowing through it is lost in the form of heat. Locating the power supply at an optimum point along the cable minimizes the total electrical energy "line losses" during the acceleration and subsequent deceleration of the launch system.

Electrodynamic Tethers

Electrodynamic tethers are thin cables made of an electricity-conducting material, typically a metal. If we deploy such a tether from a satellite in a low Earth orbit, it will tend to orientate itself vertically due to the gravity gradient explained earlier (see Momentum Exchange). It is not even really necessary to have another satellite on the other end of the tether; the tether itself has a mass and therefore experiences the same forces as the second satellite in the momentum exchange tether system example.

You may remember from high school physics that when you move a conducting wire through a magnetic field, a voltage is induced along the wire. This voltage depends directly on the magnetic field strength, the velocity, and the length of the wire. Now imagine our conducting tether moving through Earth's magnetic field at about 8 km/s (5 miles/s). Such a system can induce several hundreds of volts per kilometer of tether! To make this useful, we need to have an electric current, which means we need electrons going in at one end of the tether and getting out at the other end, being driven through the wire by the voltage. You can think of a voltage as a height difference, such as between a mountaintop and a valley. Only when we add water will we get a stream flowing down the mountain (i.e., a current).

Fortunately, there are plenty of free electrons available in the thin upper part of the atmosphere, called the ionosphere, where ultraviolet and x-ray radiation from the Sun knocks electrons from atmospheric gas molecules. The voltage along the tether will attract these free, negatively charged electrons at its positively charged end (called the anode). The electrons will then move through the cable to be expelled at the other end by a so-called plasma contactor (also called the cathode). The conducting tether and the less conducting ionosphere thus together form a closed electrical circuit, making the flow of electricity possible.

To facilitate the collection of electrons, the anode can be a large metal sphere. However, an uninsulated tether will be able to collect free electrons over a large part of its length instead of just at its tip. It prevents the piling up of electrons in a small area, which would block the way for other electrons (since electrons have the same electric charge, they repel each other) and thus increases the tether's efficiency. This "bare tether" concept was first proposed by Juan SanMartín, a professor of physics at the Polytechnic University of Madrid, Spain.

The induced current flowing through a conductive tether will interact with Earth's magnetic field to cause what is called a Lorentz force. The laws of electromagnetism state that this force will always have a direction that opposes the motion of a wire going through a magnetic field, which means it will try to slow it down (and thus also decelerate the attached satellite). Using this "electromagnetic drag," we can lower the orbit of a satellite or even completely de-orbit it so that it falls back into the atmosphere to burn up or land on Earth (Fig. 1.14).

In terms of energy, the kinetic ("movement") energy of the satellite and tether system orbiting around Earth is converted into electric energy. As the current flows through the tether, heat is generated because of the electrical resistance of the conductive tether material (so-called ohmic heating). This heat is then dissipated into space as infrared radiation. The result is that the tether system loses (kinetic) energy, and thus slows down. The main benefit with respect to an aerobraking tether, which can also be used to slow down a

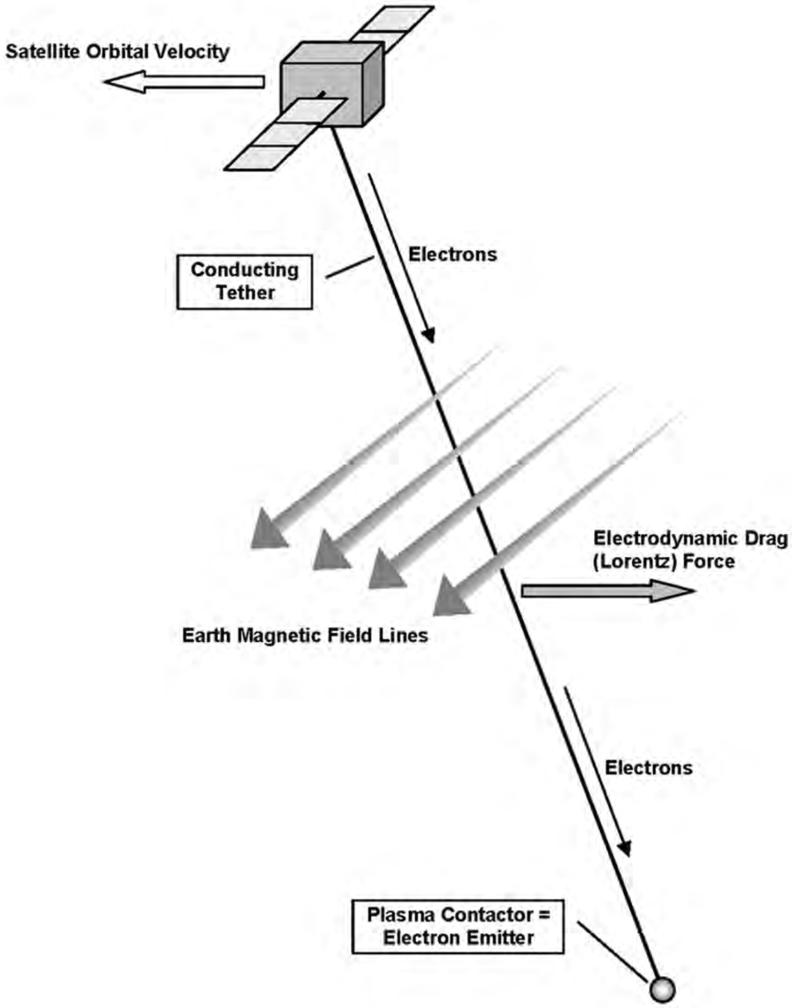

Figure 1.14: The principle of an electrodynamic drag tether.

spacecraft, is that the electrodynamic tether does not have to be lowered as deep into the atmosphere.

In principle, electrodynamic drag tethers can also be used to generate electrical power in space. A 20-km-long (12-mile-long) wire in a low Earth orbit can produce up to 40 kilowatts of power, enough to run 400 light bulbs of a 100 watts each or, more suitably, a sizable space station. However, since the energy conversion means that the orbit of the satellite is lowered, it cannot be used for extensive periods of time without firing rocket thrusters to compensate for the electrodynamic drag force. Of course, burning

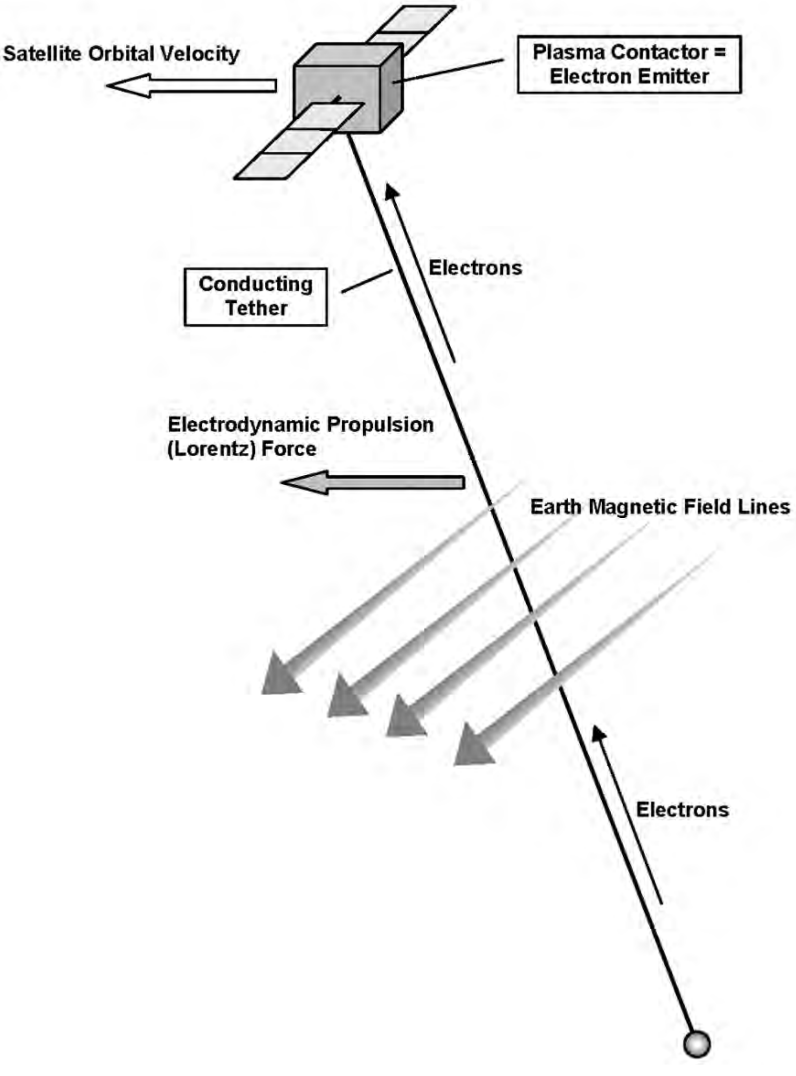

Figure 1.15: The principle of an electrodynamic propulsion tether.

propellant to generate electricity is not an efficient way to power a satellite that could use free solar energy instead (by means of solar cells). Nevertheless, electrodynamic tether power generation could be useful for generating short bursts of electrical energy, for instance when needed for high-energy but short duration experiments involving powerful “lidars” (instruments similar to radar but using laser light instead of short wavelength radio waves).

Virtually the opposite of an electrodynamic drag tether is the related electrodynamic propulsion tether. In this case electrical power supplied by a set of solar arrays is used to run a current through the tether. If the direction of the current is opposite to the direction it would flow in case of an electrodynamic drag tether, the resulting Lorentz force will also work in the other direction and thus push the spacecraft rather than slow it down. It is similar to the winding in an electric motor pushing against the magnets of its armature, causing a torque force. Such a tether can then be used to accelerate a satellite and send it into another orbit. Effectively, electrical energy (from the Sun, in case solar arrays are used) is added to the tether system and converted into kinetic (movement) energy, making the spacecraft go faster (Fig. 1.15).

Both the “drag” and “propulsion” variants of the electrodynamic tether can in principle replace traditional propulsion systems onboard spacecraft. They can change the orbit of a satellite without the need for any propellant, which means important mass savings. The orbit of a satellite also could be changed as many times as needed if there is no dependency on a limited amount of propellant. Furthermore, the propulsion version can be used to keep low-orbiting satellites, which are exposed to minute but continuous aerodynamic drag, at a proper altitude and thus prevent them from falling from the sky. These are potentially huge benefits, but electrodynamic tether systems only work when orbiting within a sufficiently strong magnetic field. Around the Moon, for example, they are useless because the Moon has virtually no magnetic field.

Serious work on electrodynamic tethers has been going on since the 1970s, when Mario Grossi of the Harvard-Smithsonian Center for Astrophysics and Giuseppe Colombo of the University of Padua in Italy first conducted scientific research on what was then a very novel technology.

Electrostatic Tethers

Electrically conducting tethers can also be used for purposes other than changing orbits of satellites and electrical power production. One interesting concept is to use them to remove charged particles from the vicinity of Earth.

The Sun sends out a continuous stream of electrons and ions. Ions are atoms that have an electrical charge because they contain too many or too few negatively charged electrons to compensate for the number of positively charged protons in the atom’s nucleus. Earth’s magnetic field traps these charged particles like a magnet attracts iron dust, and keeps them locked up in the so-called Van Allen radiation belts. The belts were discovered by James

Van Allen, using data from the first American satellite, Explorer 1. The particles in the Van Allen belts pose a serious threat to satellites and people venturing into them. They can upset and even destroy sensitive onboard electronics, degrade spacecraft materials, and cause biological damage in the cells of astronauts' bodies.

The Van Allen belts vary in intensity with latitude; they are thickest above the equator and diminish in the direction of the North and South Pole. Moreover, the intensity varies with altitude, so that spacecraft in the most useful orbits relatively close to Earth and satellites in high orbits such as GEOs are fortunately little affected. However, satellites transferring from low orbits to higher orbits such as GEOs or on their way to other planets necessarily have to fly through the belts.

However, low Earth orbit satellites are not completely safe. Earth's inner Van Allen belts are symmetrically aligned with the planet's magnetic axis. However, this axis is tilted with respect to Earth's rotational axis by about 11 degrees. In addition, the magnetic axis is offset from the rotational axis by some 450 km (280 miles). Due to this offset and tilt, the inner Van Allen belt is closest to Earth's surface over the southern Atlantic Ocean. The consequence is an increase in radiation levels in region off the east coast of South America. This area is called the South Atlantic anomaly and can affect satellites in otherwise safe, low orbits between altitudes of about 500 and 1000 km (300 and 600 miles) (Fig. 1.16).

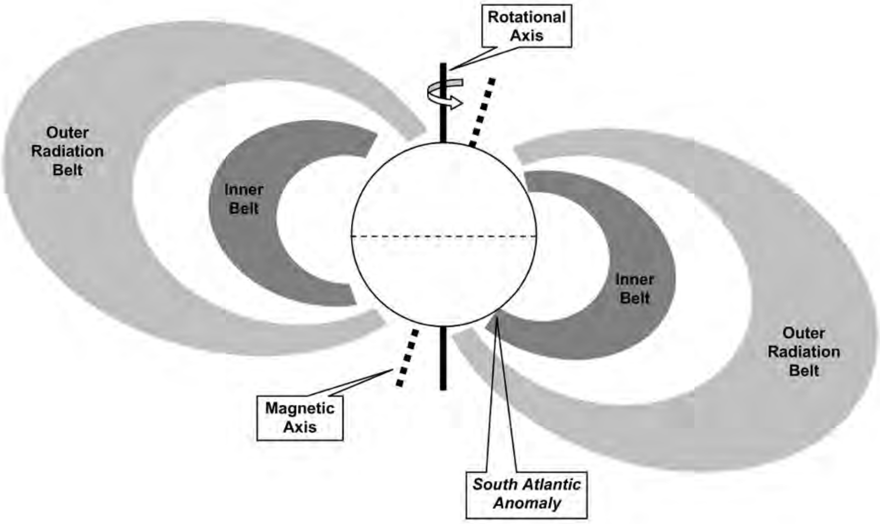

Figure 1.16: A cross section of the Van Allen radiation belts and the location of the South Atlantic anomaly.

The explosion of an atomic bomb at high altitude could create an artificial and even more dangerous radiation belt. The highly energetic particles ejected by such a nuclear explosion would threaten satellites that otherwise orbit in low-radiation, low Earth orbits. Such a weapon could thus be used to destroy military observation and communication satellites. In the process it would also damage other satellites, nonmilitary and those of neutral countries, in orbits affected by the artificially created radiation. Experiments performed in the 1960s with nuclear bombs detonated in space showed that the lethal radiation belts can persist for many years (the testing of nuclear weapons in space has since been prohibited by the United Nations Outer Space Treaty of 1967).

It would be nice to be able to flush the Van Allen belts of charged particles, and it may be especially important to be able to get rid of any artificially created radiation belts as soon and as fast as possible. This could be done by employing electrically conducting tethers of several tens of kilometers in length into orbits that bring them into the radiation belts. When these are charged to very high voltage levels, the electromagnetic fields thus generated can scatter the energetic radiation particles, over time sending many of them out of the radiation belts (into the atmosphere or further into space) and thereby lowering the radiation levels.

Beanstalks

All the tether applications described up to now work only in space. However, the most difficult and costly part of spaceflight is leaving Earth, and that is where the highest potential benefit of replacing conventional rockets with a tether system can be found.

In the earlier explanations about how orbits work, satellites were launched with a hypothetical cannon on top of a tower that reaches all the way into space. In reality this would not work, because we are not able to build towers that are several hundred kilometers high. Moreover, the extreme acceleration needed to speed a normal satellite up to orbital velocity over the length of the barrel of a cannon would result into very flat and very damaged spacecraft.

Instead, we use rockets to carry satellites above the atmosphere and to relatively slowly increase their velocity. This requires a huge amount of propellant, and in addition large and heavy tanks to contain all that propellant plus all kinds of other rocket engine equipment. Every kilogram of satellite put in low Earth orbit requires about 100 kg of propellant and rocket hardware. This is not very economical, especially because in order to keep the overall rocket weight within reasonable limits there is generally no mass left that could be allocated to wings and heat shields. Without these additions, there is no way to bring the system back to Earth once its cargo has been delivered. Rockets are therefore mostly single-use, expendable systems. This is like using an airplane only once, and buying a new vehicle for each trip—a rather inefficient way of blasting ourselves into space.

The Space Shuttle is partly reusable, but the intensive maintenance it requires has led to its being the most expensive launch vehicle. A launch is estimated to cost around half a billion dollars, while a launch with an expendable rocket with comparable payload mass such as the Ariane 5 costs about a third of that. The development of more modern, more economical reusable launch vehicles continues to struggle with mass growth and cost problems, and no revolutionary launch vehicle technology solution is likely to be available in the foreseeable future (see Chapter 2).

But what if we just completely dispense with rockets and use something completely different to get into orbit—something like an extremely long tether to climb up into space, for example? This seems to be a rather ludicrous idea, but considerable thinking by various space organizations has already been put into this concept. Even the National Aeronautics and Space Administration (NASA) has studied the "space elevator" concept and found it to be challenging but not necessarily unfeasible.

The general idea involves a cable of an incredibly strong material that directly connects an orbital space station with Earth's surface, kind of like a bridge or beanstalk into space. The center of mass of the system would have to be positioned in geostationary Earth orbit, where its orbital rotation is 24 hours and it thus remains above the same point on the equator as Earth rotates around its axis. In this way, the tether could be connected to an earthbound base station located on a fixed position somewhere on the equator.

With the center of mass in any other orbit, the system would move too fast or too slow with respect to Earth's surface, and the cable would break. To have the system's center of mass in geostationary Earth orbit, a countermass would be needed at a higher altitude to compensate for the mass of the cable going down to Earth; because the countermass would be moving too fast for its higher orbit, it would pull on the tether and keep it taut. In other words, the centrifugal force on the part of the cable above the geostationary point would balance the gravity force pulling down the lower part (Fig. 1.17).

Electromagnetically suspended and propelled elevators or mechanical climbers (often called "lifters" by space elevator enthusiasts) could be used to shuttle between the surface and the space station, without the need for any form of rocket propulsion. Based on the amount and price of the energy

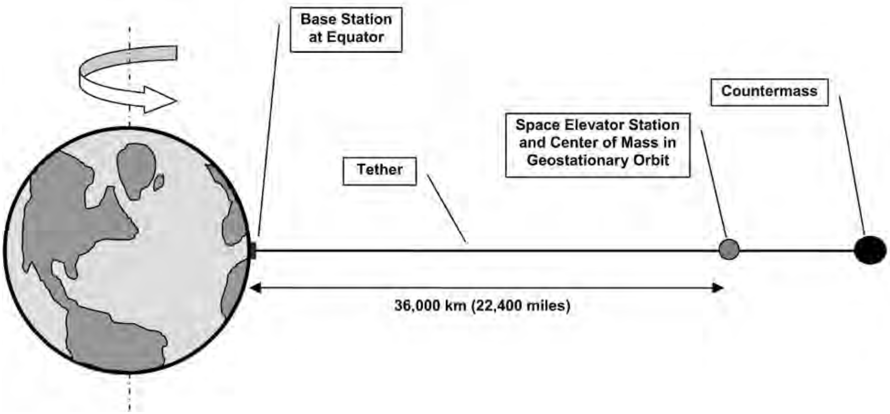

Figure 1.17: Schematic of a space elevator (not drawn to scale).

needed to bring something up the tether into space and early estimates of the fixed operations cost of a space elevator, the cost for bringing cargo into orbit could be less than $150 per kilogram—about a factor 100 lower than is currently the case. A person with luggage could then make a trip into space for only $15,000.

If a space station would be put in the elevator system's center of mass, that is, in geostationary Earth orbit, it would be located at an altitude of 36,000 km (22,000 miles). Preliminary estimates suggest that an electromagnetically propelled elevator may take more than a day to reach such an altitude, and a mechanical climber may take more than a week. Elevator shuttles for people would thus have to be equipped with sleeping facilities, a kitchen, toilets, and so on, but for uncrewed spacecraft and cargo containers the long travel time would not matter. The low acceleration levels and the lack of noisy, violently vibrating rocket engines would actually make the transfer much easier on satellites and other equipment, allowing them to be constructed less robustly than required for a rocket launch. This could result in less expensive spacecraft.

The orbital station at the geostationary point could be made very large, as construction materials from Earth could be transported up easily and at low cost by the elevators. The station could incorporate satellite launch facilities, telecommunications equipment, astronomical observatories, Earth remote sensing instruments, and space tourist hotels with microgravity sports facilities and rooms with magnificent views of Earth and space.

Mass growth of the station would have no effect on the stability of the space elevator, because it is located in the geostationary point. That is where the system's center of mass needs to be, and where all the mass is effectively in orbit and thus does not pull on the cable in any direction.

However, any mass growth by the construction of facilities or installation of additional cables below the geostationary point would need to be compensated for by putting additional mass at the upper, countermass end of the cable. Without this, the space elevator would be pulled down by its own weight.

Apart from offering an easily accessible microgravity space station at geostationary orbit altitude, and possibly stations below and above this point, the space elevator would greatly facilitate the launching of free-flying satellites. To put a spacecraft in geostationary orbit, it could be transported up the cable with a cargo elevator, and then simply released from the center mass station. It would then immediately have the right velocity to stay in orbit, and require only small amounts of propellant to reach the intended geostationary orbit position (which is fixed with respect to the surface of Earth). When satellites are released above the geostationary point, their velocity will be too high for their altitude. The result will be an elliptical orbit, with the launch altitude being the perigee. Sufficiently high up the elevator, a spacecraft could even move off at interplanetary velocity and be sent on its way toward other planets. We could think of a space elevator as a giant slingshot hurling spacecraft into deep space.

The feasibility of the space elevator concept depends mostly on the availability of materials that can withstand the incredible forces on the cable. Steel is too heavy and by far not strong enough. Cables made from revolutionary materials based on so-called nanotubes are required. Carbon nanotubes are tiny cylindrical molecules of carbon, stiff as diamond yet a hundred times stronger than steel at one sixth the weight. Unfortunately, the performance of cables we can currently construct out of carbon nanotubes is not yet up to space elevator standard (see Cable Material in Chapter 7).

The space elevator is the most exciting, most inspiring, and potentially most important application of space tethers, but also the most complex and most difficult to develop. Chapter 6 is devoted to this idea.

Disruptive Technology

2

In their 1995 article, “Disruptive Technologies: Catching the Wave,” Harvard Business School professors Joseph Bower and Clayton Christensen define two categories of new technology: sustaining and disruptive. Sustaining technology relies on incremental improvements to an already established technology. A good example is the conventional petrol engine used in automobiles; the principle on which it works has not changed in over a hundred years, but a modern car engine is much more reliable and efficient than that of a 1908 model-T Ford. Disruptive technology, on the other hand, is a revolutionary technology that suddenly, and often unexpectedly, displaces an established technology. Take, for instance, the rapid market takeover by digital cameras at the expense of long-proven and firmly established film-photography technology. According to Bower and Christensen, disruptive technology initially often lacks refinement, appeals to a limited number of people, and may not yet have a proven practical application (the idea is further developed in Christensen’s 1997 best-selling book, *The Innovator’s Dilemma*).

Tether technology has the potential to be a disruptive technology; if it works as advertised, it could radically change spaceflight and make conventional rocket propulsion systems largely obsolete. If so, it would not be the first time in history that an experimental technology totally replaced older, much better established means of transportation.

New Machines

After thousands of years of development, by the 19th century sailing ships had reached an incredible level of sophistication. They were fast, their rigging could cope with a variety of wind conditions, and their crews were trained to run the ships as best as possible. Then came the steam engine. At first, ships powered by steam could not really compete with sailing, because the machines were tricky to run, the paddles initially used to propel the

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vessels were inefficient, and there was no worldwide infrastructure of fuel depots to enable an adequate range. Many were skeptical of the need for this new technology and doubted that the potential advantages would outweigh the investments. Was it really worth the trouble of completely converting the established and trusted system of sailing ship transportation? However, as the technology matured, steam boats quickly made the old sailing vessels obsolete. They became faster, were independent of the wind, and required much smaller crews, thus enabling rapid and predictable transportation at lower costs.

Later, in the early 20th century, cars were initially also greeted with skepticism. The first automobiles were expensive, broke down frequently, and could not travel on rough roads like horses could. Nor were they able to carry the huge amounts of cargo transported at high speed by steam trains. Nevertheless, eventually the car made it possible to transport people and goods in quantities and at an efficiency that would be impossible to reach with horses. Just think of how much food and stable space would be needed if everybody still used horses instead of cars, and how much slower local transportation would be. In addition, cars, unlike trains, are not limited to rails and can thus get to any village. They can be used by the driver and a few passengers, or even no passengers, while railroads are economical only if transporting large numbers of people or large amounts of cargo. The modern, large-scale economies needed to support the billions of people now inhabiting our planet could never be supported by horsepower alone or by trains alone.

The steamship and the car are just two examples of new technologies that dramatically disrupted the status quo, even when at the time their use did not seem to be required and their benefits seemed insufficient to warrant further investments. Space transportation now appears to be ready for a revolution as well. Even though conventional rocket propulsion can support all we do in space and has only relatively recently reached its maturity and become trusted, the limits of its performance capabilities and economic possibilities are already in sight.

Rocket Propulsion Limits and Limitations

Current space missions are heavily dependent on chemical rocket propulsion for the launch into space, for changing orbits, and for attitude control.

For the launch, rockets with chemical propulsion engines are used because there is simply no other way to put anything in orbit. Launcher technology has improved a great deal over the last 60 years, so that rockets can now transport their payload more precisely to the desired orbit, are able to place multiple satellites into different orbits, and to do this with increased reliability and safety.

However, improvements in actual payload capability and launch cost have not been dramatic. Rocket engines have become somewhat more efficient, but the increases in thrust per amount of propellant have been relatively small. It appears we are currently reaching the limits of chemical rocket propulsion performance; any small increase in efficiency now requires such large amounts of development work, time, and money that it is often not worth the effort. In addition, the structural masses (the mass of the propellant tanks and support structures) of rocket stages have not improved much over the last 50 years. The launchers in use today are very similar to those that were developed in the 1950s to throw nuclear bombs at other countries. Modern rockets such as the American Atlas V and the Russian Soyuz are even direct descendants of early intercontinental ballistic missiles (Fig. 2.1).

All in all, the total mass that a certain type and size of launcher can put into a certain orbit has not improved very much since the 1960s. Looking, for example, at the total satellite payload mass that launchers can put into a low Earth orbit (LEO) as a percentage of their total lift-off mass, it becomes clear that this number has been close to 3.5 percent for the last 40 years or so (LEO extends to an altitude of about 2000 kilometers, or 1.240 miles). For geosynchronous transfer orbit (GTO) payloads, that percentage has been a steady 1.5 percent for the same period. A GTO is an elliptical orbit in which a geosynchronous orbit [GEO] satellite is initially launched in order to reach GEO altitude; at the GTO's apogee, a rocket motor is ignited to place it in a circular, geosynchronous orbit. For many modern launchers these percentages are even lower, depending on what the rocket is designed to do and how sophisticated it is (Figs. 2.2 and 2.3).

All launchers except the Space Shuttle are still of the expendable type, meaning they can be used only once. They drop off their empty stages along the way as a means of getting rid of dead weight. These stages then splash into the ocean or burn up in the atmosphere; outfitting them with retrieval equipment such as parachutes or deployable wings would make the launcher too heavy. Once the satellite cargo has been put in orbit, no part of these expensive machines is left for reuse.

Thus, this is an extremely expensive way to transport things. A medium-sized launcher such as the Russian Soyuz-Fregat can put a 1100-kilogram (2400-pound) spacecraft on a journey to Mars, but in doing so it throws away 26 metric tons (57,000 pounds) of precious rocket hardware (as well as

Figure 2.1: A Soyuz launcher, a direct derivative of the rocket used to launch the first satellite, Sputnik, and the first cosmonaut, Yuri Gagarin, is still being used to launch people and satellites. (Courtesy of the European Space Agency [ESA].)

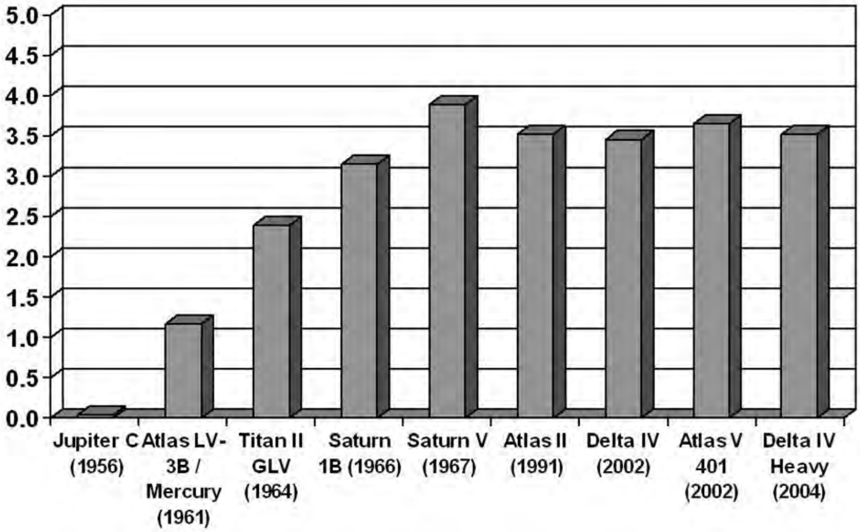

Figure 2.2: Payload mass as a percentage of a rocket's total lift-off mass, to an optimum low earth orbit (LEO), which is different for each launcher and launch site. The launchers shown represent the best of their generation in terms of payload mass to LEO.

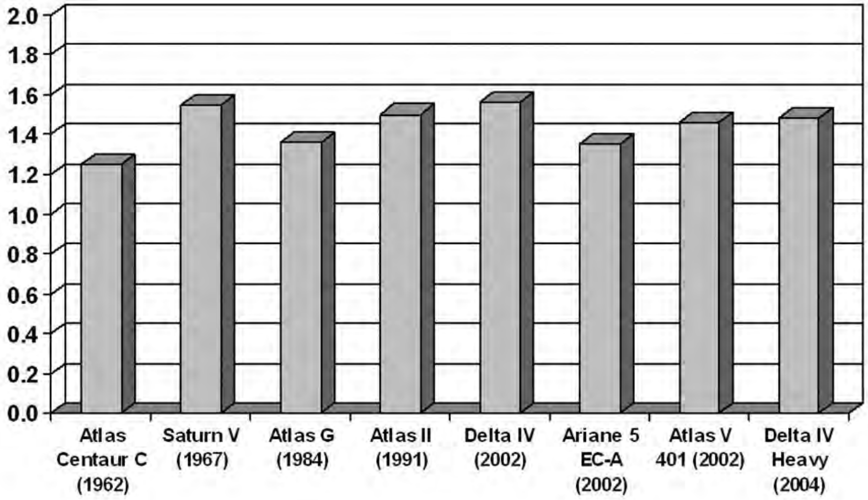

Figure 2.3: Payload mass as a percentage of a rocket's total lift-off mass, to a geostationary transfer orbit (GTO). The launchers shown represent the best of their generation in terms of payload mass to GTO.

289 metric tons (640,000 pounds) of propellant, but that is relatively inexpensive). A Soyuz-Fregat launch therefore costs on the order of $45 million, which is actually relatively cheap compared to most European and United States rockets. Improvements in how we develop, produce, and operate launchers can still decrease launch costs somewhat, as shown by SpaceX with its Falcon series of launchers, but we should not expect dramatically lower launch costs per kilogram satellite in orbit with any new expendable launchers.

An obvious way to lower launch costs is to reuse rockets. Instead of having to pay for a completely new one every time we need to put up a spacecraft, we would then only need to pay for the propellants, operations, and maintenance of the launch vehicle, such as with an airplane. Planes are not thrown away after each flight.

The reason that expendable rockets are still the norm is that we have not had much success developing reusable systems. To make a launch vehicle capable of being used again, it needs additional equipment to return to Earth. Heat shields, wings, parachutes, and additional propellant for landing make reusable systems relatively heavy. As the satellites on top of expendable launchers comprise only a few percent of the total launch mass, the mass available for useful payload is easily eaten up by additional components added to make the system reusable. The fact that rocket engine efficiency and structural mass reductions are already close to their achievable limits means that it is very hard to compensate the mass growth in a reusable launcher design. Many concepts for reusable systems, therefore, would be capable only of launching and flying back the bare vehicle itself, without any mass allocation to spare for spacecraft cargo such as satellites and space station modules.

Reusable launchers are also more difficult and therefore more expensive to develop than expendable launchers. On top of the difficulty of developing something that can go into orbit, now the vehicle also needs to be designed to come back, which involves reentry into the atmosphere, a descent phase, and a soft landing. Furthermore, the use of such launchers requires not only a launch pad but also the development of additional infrastructure, such as a safe landing area, vehicle and engine maintenance buildings, and logistics facilities to store and manage the distribution of spare parts.

Instead of these recurring costs for a reusable system, every expendable launch involves a brand new vehicle, and therefore operations are limited to the launch preparations and the actual flight. In addition to this, however, a reusable launcher requires inspection and maintenance before each subsequent mission. The operations costs for reusable systems are therefore also higher than in the case of expendable rockets. The Space Shuttle orbiter, for example, excluding the effort for its main rocket engines, requires a maintenance team of some 90 people, each working about 1000 hours after each mission. This costs about $8 million per flight on maintenance labor alone. Together with the maintenance hours on the three large Space Shuttle main engines and the two reused solid rocket boosters, this represents a huge amount of money that does not need to be spent when using expendable, single-use rockets. Moreover, the Space Shuttle system is not fully reusable: the large brown external tank is discarded during each flight, so a new one is needed for every mission.

The higher development, infrastructure, and maintenance costs mean that operating reusable launchers can result in lower launch prices only if they make many flights each year. It is just like with commercial airlines, which need to keep their planes in the air for as many hours as possible to keep costs down. This requires short maintenance cycles; otherwise a large and therefore expensive fleet of vehicles would be needed. To justify launching many spaceflights, we also need a large number of customers who require the launch of many more payloads than is currently the case. The launch market will significantly increase in size only if launch prices drop dramatically, which in turn requires efficient reusable systems with little maintenance needs. This is a really difficult catch-22 situation: launches could become cheaper if there was a sufficiently large market, but this market will not grow until launch costs drop significantly.

The maintenance of the (partially) reusable Space Shuttle turned out to be so time-consuming that the initial expectations of launching some 60 missions per year never became a reality; in a good year, the shuttle is launched about six times. The high maintenance and replacement costs and the low launch rate have resulted in very high launch costs. Before the Columbia disaster, a Space Shuttle launch with all its complicated pre-launch activities and human spaceflight equipment was costing on the order of $300 million to $500 million per flight. The additional safety constraints put in place after the loss of Columbia probably put the current cost way over half a billion dollars per flight. This makes the Space Shuttle the most expensive launch vehicle, both in total launch price and in cost per kilogram payload put in orbit. For the current relatively few satellite launches per year, it is cheaper to use expendable, one-shot rockets. The reason that the Space Shuttle is still in use despite its disadvantages is that it is the only vehicle the United States has available for human spaceflight.

In fact, for the relatively few crewed missions it foresees to the Space Station in the 2010s and to the Moon in the 2020s, NASA has found that it will be less expensive to operate classic expendable rockets and capsules rather than some kind of reusable shuttle system. NASA has therefore decided that the successor of the Space Shuttle to launch astronauts, the Ares I launcher, will be an expendable system that is not too different from the rockets used to launch the early pioneering astronauts of the Mercury, Gemini, and Apollo space programs in the 1960s. Ares I will be topped with an Orion capsule that may be partly reusable, but is otherwise very similar in design to the Apollo Command and Service Module combination of 40 years ago (Fig. 2.4). For launching large cargoes such as lunar base modules, NASA will develop the Ares V, which will be a mostly expendable rocket (only the solid rocket boosters derived from the Space Shuttle system may be reused) (Fig. 2.5). New versions of the Ariane, Atlas, Delta, and Soyuz rockets are also still being developed, and it does not look like these expendables will become obsolete and replaced by reusable launch vehicles anytime soon.

Radically lowering launch prices for traditional rocket propulsion systems, even by means of reusable equipment, is extremely difficult. The SpaceX company in the United States is now offering its expendable Falcon 1 launcher, and the advertised launch price of $7 million means a significant drop in price with respect to that of the competition, which is about double for the same payload. Using larger successors of Falcon 1, SpaceX believes it will be able to offer prices on the order of $1000 per kilogram payload in low Earth orbit by 2010. Since the current cost is about $5000 per kilogram for large launchers (and about $10,000 per kilogram for small launchers with small payload capabilities), this would mean a significantly lower launch cost. However, it is still a lot of money. For example, taking into account also the mass of the spacecraft, flying as a space tourist with SpaceX would still mean a ticket price of about $1 million to $1.5 million—much less than the $20 million paid by recent space tourists flying with the Russian Soyuz to the International Space Station, but still a lot more than most people can afford.

Some private companies are developing reusable launch vehicles, having determined (or hoping) that with currently available technology it may yet be possible to develop cost-efficient reusable launch vehicles. Government space agencies such as the European Space Agency (ESA) and NASA have not completely given up on reusable launchers either. Smart concepts such as the suborbital hopper may still make lower launch costs possible. A hopper is a reusable vehicle that does not accelerate all the way up to orbital velocity but delivers payloads in space at almost orbital speeds. Such a launcher saves huge amounts of propellant by not having to boost its own mass into orbit; the mass of an additional booster stage required to give the cargo the bit of extra speed it needs is very limited in comparison. Also, future technology such as rocket and jet engine combinations able to make use of the oxygen in the atmosphere for important parts of the flight, and thus requiring less onboard propellant, may enable the development of

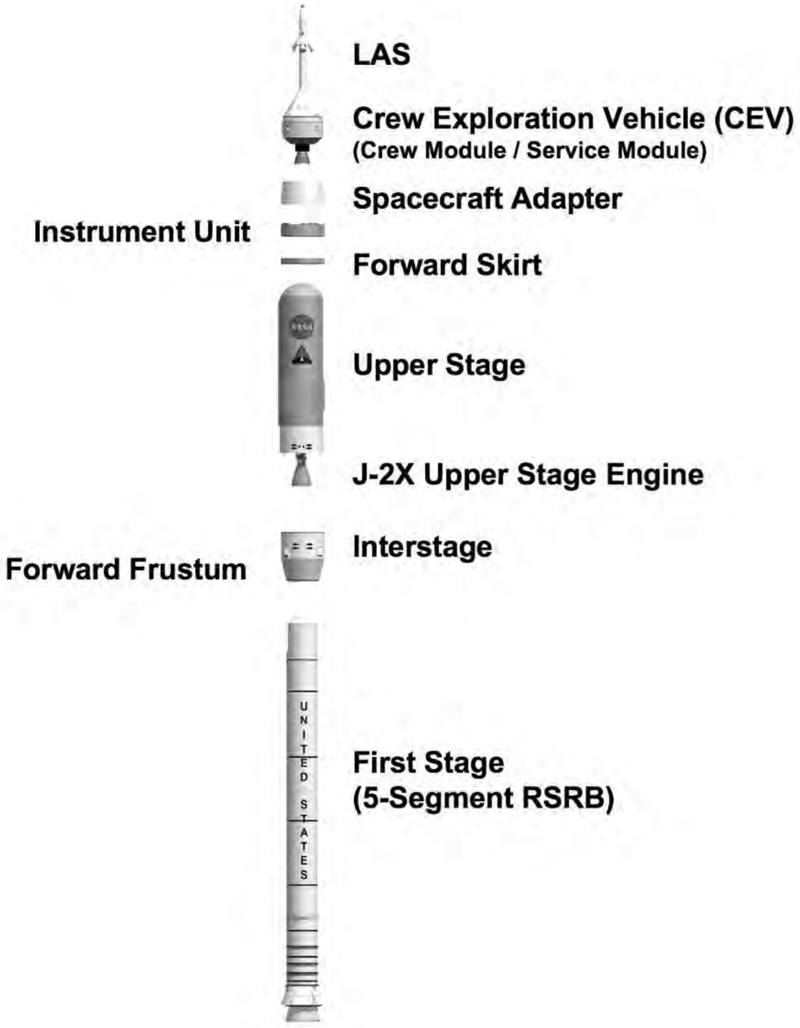

Figure 2.4: The Ares I launcher will consist of an extended Space Shuttle solid rocket booster and a new upper stage, and will not be reusable. (Courtesy of NASA.)

efficient space planes. If novel concepts and technology can drop launch prices to levels that make it affordable for smaller countries and organizations to launch satellites and people into space, the market may grow enough and launch rates may increase sufficiently to warrant the development of even better reusable systems.

However, a completely different new technology may be needed to radically lower the costs of access to space. Even if new and reliable launch systems reduce these costs by a factor of ten, it may take more than that to

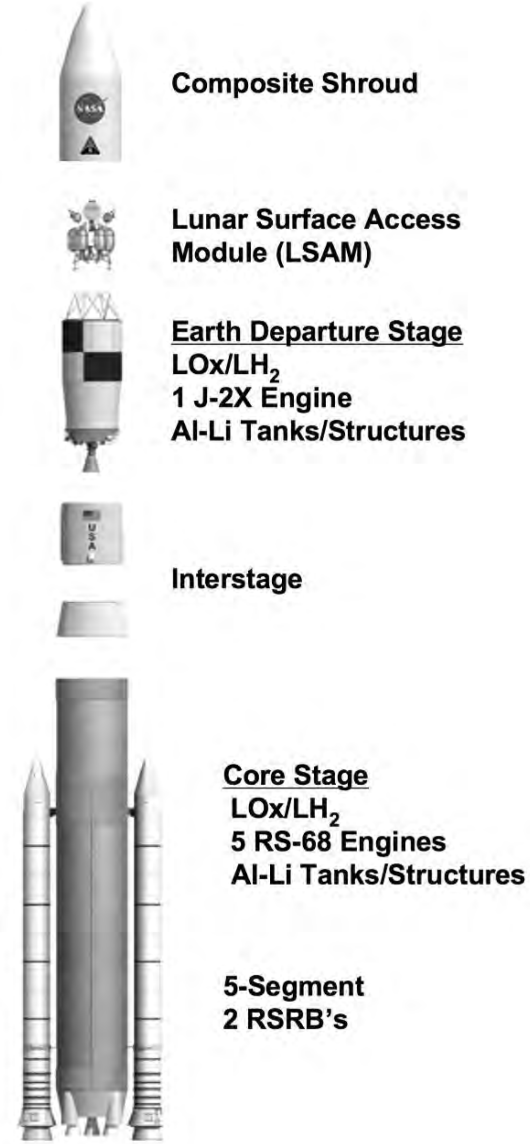

Figure 2.5: The Ares V will be a heavy lift, nonreusable launcher for large payloads. (Courtesy of NASA.)

make new applications such as lunar mining, microgravity industries, mass space tourism, and Mars colonization economically viable. Instead of $1000 per kilogram payload in low Earth orbit, it would take prices on the order of $10 per kilogram or less to make the cost of a flight into space comparable to that of transportation by airplane.

Rocket propulsion is not only used to launch things, it is also the main means for maneuvering and changing orbits, and for controlling the attitude of spacecraft. Relatively large thrusters are used for trajectory adjustments, changing orbit altitude and inclination (the angle of the orbit with respect to the planet's equator), and braking (for getting into orbit around another planet when arriving there with too high velocity from an interplanetary transfer flight). Smaller thrusters, often on the order of a couple of tens of newton force, are used for attitude control and delicate maneuvering (with 1 newton being equivalent to the force that gravity exerts on a 100-gram [0.2-pound] mass on Earth's surface). The mass of the required propellant, rocket thrusters, tanks, pipes, and valves often comprises a large part of the total spacecraft mass.

The Venus Express spacecraft of the ESA, for example, had a total mass of about 1270 kg (2800 pounds) when it was sent on its way. No less than 570 kg (1260 pounds) of this was propellant, while the propulsion hardware had a mass of 60 kg (130 pounds); the propulsion subsystem thus accounted for about 50 percent of the total mass!

Even when orbit adjustments are not needed, the attitude control (stabilization) and orbit maintenance of satellites requires a lot of propellant. About 30 percent of the total mass of a typical geostationary communications satellite with a lifetime of 15 years consists of propellant for so-called station keeping.

Electric Propulsion

There is a more mass-efficient type of propulsion that requires much less propellant for the same spacecraft and mission. Rather than ejecting hot gases that are products of a combustion process, electric propulsion systems eject charged particles using electromagnetic forces. In an "ion engine" the atoms of an inert gas, usually xenon, are ionized and shot out at a much higher velocity than in a normal rocket engine; while an engine burning liquid propellants may shoot out hot gases at 4.5 kilometers per second (3 miles per second), an ion engine expels its charged atoms at more than four times this speed. This makes ion engines much more efficient, giving the same impulse and therefore enabling the same increase in spacecraft orbital velocity or rotational velocity management (in the case of attitude control) for much less propellant. Ion engines are already widely used as attitude control thrusters for large communications satellites and are now also employed as a means of propulsion for interplanetary missions (Fig. 2.6).

However, electric propulsion also has disadvantages. In conventional

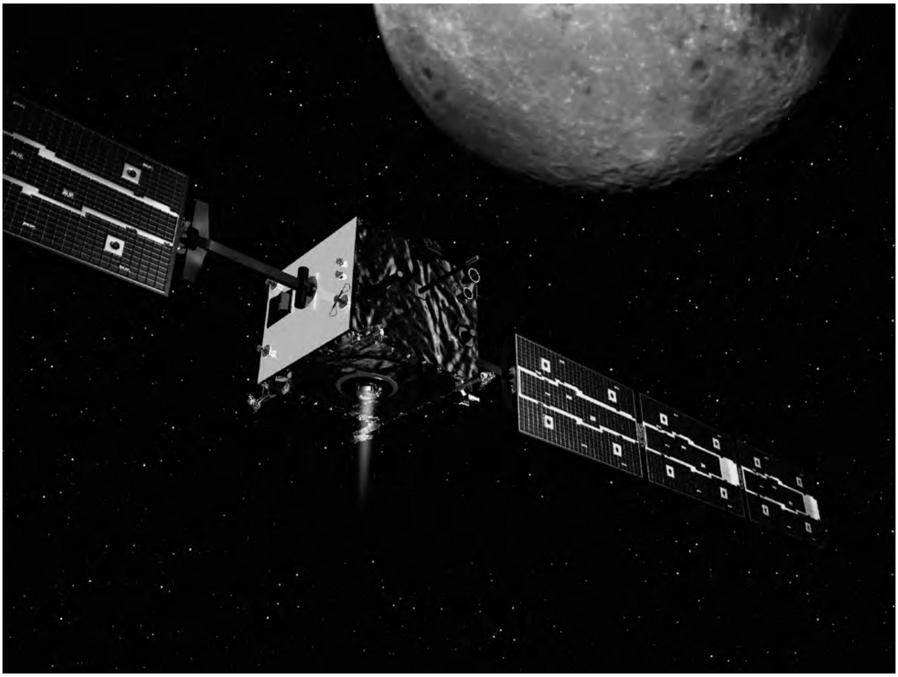

Figure 2.6: Artist's impression of ESA's SMART-1 spacecraft, which tested solar-electric propulsion by using it to fly to the Moon. (Courtesy of ESA.)

rocket engines the energy that propels the gases out of the nozzle at high speed comes from the combustion of chemical propellants. An ion engine requires a strong magnetic field to charge and accelerate gas atoms, and for that it needs electricity. This is supplied by the Sun through the solar arrays, which is why the concept is usually referred to as solar electric propulsion. It means that spacecraft with electric propulsion require larger and thus heavier solar arrays than similar probes with chemical propulsion systems.

More serious is the problem that ion engines can produce only tiny thrust levels, on the order of the weight of a sheet of paper. Electric propulsion, therefore, can be used only in space; on Earth an ion engine is not even capable of lifting its own weight, let alone a spacecraft. The extremely low thrust means that a spacecraft with ion engines can manage only very small acceleration levels, on the order of a fraction of a millimeter (a hundredth of an inch) per second every second. To increase the velocity by 1 meter per second can take more than an hour. Interplanetary probes using electric propulsion thus take much more time to reach their target, which increases operations costs and the wear and tear on spacecraft equipment. Moreover, the tiny thrust levels mean that ion engines have to run for much longer durations than conventional engines, which increases the risk of failure. The ESA's SMART-1 spacecraft, a lunar satellite whose main mission was to flight test solar electric propulsion for future deep space missions, took 16 months and 332 ever-widening orbits around Earth to reach the moon. With some short boosts from a conventional rocket engine it would have taken a similar probe only a couple of days to get there.

With respect to conventional propulsion systems, solar-electric systems trade high thrust levels for increased efficiency and therefore lower propellant consumption, resulting in a lower propellant mass (and thus a lower total spacecraft mass or the possibility to incorporate more scientific equipment). Ion engines are thus very efficient, but using them means considerably stretching the duration of interplanetary transfers and orbit adjustments, and precludes the use of quick and sudden maneuvers. This makes solar electric propulsion fairly useless for crewed space missions, which require transfers that are as short as possible to limit adverse physiological and psychological effects and to minimize the amount of water, air, and food needed onboard.

Solar Sailing

Using even less propellant than solar electric propulsion, zero in fact, is solar sailing. Rather than converting the Sun's radiation into electricity to run a rocket, a solar sail uses solar energy directly. Solar sails are large, ultralight, mirror-like sheets of extremely thin foil. As light is reflected, the light photons transfer some momentum to the sail as they "bounce" away. The result is that the light exerts a tiny force on the solar sail (a bit like making a toy car with a sail on top move by shooting little balls at it). The push is extremely small, less than a kilogram of force per square kilometer (0.8 pounds per square mile), so an enormous surface is needed to get any significant acceleration out of it. Somewhat like electric propulsion, the weak push acts continuously so that eventually a solar sail spacecraft could attain speeds several times faster than possible with traditional rockets.

The continuous force of sunlight acting on a solar sail could also be used to put spacecraft into very special orbits that are not strictly limited to the orbital mechanics rules of Newton and Kepler. Instead of following a normal orbit, a very light solar sail may "hover" in a fixed position with respect to the Sun and the stars, by balancing the Sun's gravity pull and light pressure push. In a similar way a solar sail may remain in a fixed position over the North or South Hemisphere of Earth, something that for normal satellites is only possible over the equator, in GEO (Fig. 2.7).

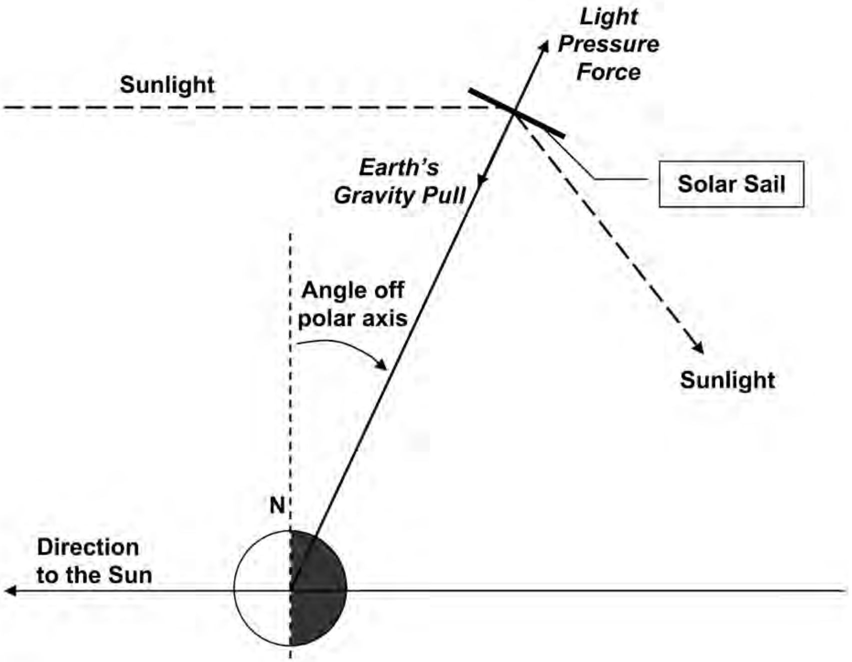

Figure 2.7: A solar sail could balance the Sun's gravity and light pressure to remain in a fixed position over Earth at high latitudes, rather than follow a conventional orbit.

A big disadvantage, however, is that the Sun needs to be close enough for the sail to receive enough light; the further out into the solar system, the lower the acceleration. Beyond the orbit of Mars acceleration levels are too low for the practical use of solar sails (which does not mean solar sails cannot fly any further; as long as they pick up enough speed in the inner solar system they can fly well beyond Mars). Powerful lasers on Earth could help push a solar sail, but a laser also loses its usefulness over long distances because the small divergence of the initially tight beam becomes apparent. Part of the laser energy then flies past the solar sail and does not contribute to the propulsive force. Another big challenge for solar sailing is how to fold the vast surfaces of ultrathin foil in such a way that it fits inside the payload fairing of a launcher, and can still be deployed without damage once in space. Attitude control of flexible solar sails is also still a challenge. Finally, travel times with huge solar sails from one Earth orbit to another or to other planets are very long.

Both NASA and ESA have made some deployment tests of small solar sails on Earth, and are studying demonstration missions to test deployment in Earth orbit. The Planetary Society, an organization of space enthusiasts in the United States, has already attempted to launch a privately financed test model, Cosmos 1. The spacecraft was designed and built together with the Russian Lavochkin Association and the Russian Space Research Institute. Unfortunately, the launch with a Volna rocket in 2005 failed and Cosmos 1 was destroyed, but the Planetary Society is preparing for a second try.

Another Way Forward

All in all, it appears there is a definite need for a more efficient and much less costly means of getting into orbit, and for more efficient ways of reaching other planets or changing orbits—methods that do not require huge amounts of propellant or take incredibly long periods of time to get up to speed and reach a destination. Several tether applications do enable quick spacecraft accelerations, by electrodynamically propelling or even throwing satellites into higher orbits.

Many space tether concepts are also fully reusable, in contrast to conventional launchers that leave a lot of waste, such as spent rocket stages falling back to Earth (sometimes with leftover toxic propellant on board) or remaining in orbit as space debris. Moreover, rockets expel gases and small particles into the atmosphere. With the current low launch rate, the effect on the environment is negligible, but if we require more frequent access to space in the future, then pollution may become an important issue. Tethers enable more sustainable spaceflight than our current propulsion technology (the United Nations defines “sustainable” as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”).

The space elevator concept has the potential to cause a revolution in human history. We have been living at the bottom of a gravity well up until now, and we only recently acquired the technology to climb out once in a while at high cost. A space elevator would provide an easy, regular, and sustainable way out of that well, allowing many people to clamber up and explore, develop, and colonize space ever further. As will be shown in the next chapters, tether technology is a possible solution for many of the most stringent spaceflight constraints.

3

Dreams and Ideas

The space tether has more often been addressed by science-fiction writers than by space engineers, and even today many of the tether's most interesting applications still seem very futuristic. However, a good number of the ideas that gained fame in imaginative stories have over time been developed into credible technical concepts. As happened earlier with rocket space transportation, space tether technology is moving from the pages of fiction into the domain of engineering.

Visions of the Future

Konstantin Tsiolkovsky is known as the "father of rocketry." He was an extraordinary Russian who lived from 1857 to 1935. He was born deaf and therefore was not able to attend elementary school. Nevertheless, he managed to teach himself physics and mathematics from books, and at such a high level that his father sent him to Moscow to study further. Sadly, because of his hearing limitations, he ended up spending most of his time in the great Moscow libraries instead of at the university. However, just as he had done before, he educated himself in the library, and managed to get a job as a mathematics teacher in the town of Kaloega in 1882.

Even as a child, Tsiolkovsky had been fascinated by rockets and their possibilities for the exploration of space. He understood that rockets are ideally suited for space transportation because they work according to Newton's principle of action equals reaction; in reaction to the expulsion of fast gas through its nozzle, a rocket is thrust forward in the opposite direction. This is similar to what happens when a person shoots a gun and his arm is pushed back as a reaction to the lightweight but very fast bullet leaving the barrel. Unlike conventional internal combustion engines or even jet engines, rockets carry their own oxygen, so they do not depend on any outside air. Rockets do not need an atmosphere to fly through and can thus operate in the vacuum of space.

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Tsiolkovsky studied the physics of rocket propulsion and formulated the famous Tsiolkovsky equation (or rocket equation) that describes how a rocket's velocity changes in relation to the efficiency of its engine and the amount of propellant it carries. The more propellant that is consumed and the higher the velocity at which it is expelled through the nozzle, the greater the increase in a rocket's velocity. In the process of consuming propellant, the rocket becomes lighter while the engine's thrust remains the same. Its acceleration therefore increases continuously, resulting in a nonlinear relationship between the rocket's velocity and the thrust duration. Tsiolkovsky's equation, which describes all of this in an elegant way, is the basis of all calculations regarding rocket propellant consumption and velocity.

In addition to rockets, Tsiolkovsky also studied and wrote about steerable airships, manned rockets, self-sustaining space stations, and spacesuits. This was something quite remarkable and even eccentric in a time before airplanes. Tsiolkovsky never built any rockets himself, but he inspired a number of young Russian rocket experimenters who in the 1930s began to build small experimental rockets (Fig. 3.1).

What is less known about Tsiolkovksy is that even while he was laying the theoretical basis for space transportation rockets half a century before such machines were made a reality, he was already contemplating the technology that might replace them: space elevators.

Tsiolkovsky visited the just-completed Eiffel Tower in Paris and started to wonder what it would take to build an elevator reaching all the way into space. In 1895 he published a book, *Dreams of Earth and Sky*, in which he described a giant tower extending out of the atmosphere all the way up to geostationary orbit at a height of 36,000 km (22,000 miles). On the top, at the end of a spindle-shaped cable, he envisioned a "celestial castle" (what we would now call a space station) that could be reached by an elevator. Tsiolkovsky named his system a "beanstalk," after the giant plant from the fairy tale "Jack and the Beanstalk." This was the first time anybody ever contemplated the concept of the space elevator, more than 110 years ago.

Tsiolkovsky correctly reasoned that the apparent gravity a person would feel on the way up into space would diminish, both because of the increasing distance to Earth as well as due to the increasing centrifugal force. He wrote, "As one went up such a tower, gravity would decrease steadily, without changing direction; at a distance of 36,000 km, it would be completely annihilated, and then it would be again detected … but its direction would be reversed, so that a person would have his head turned towards the earth." In the process, Tsiolkovsky thus discovered what we now call the geostationary altitude, the point up the tower at which the gravitational and centrifugal forces are in balance.

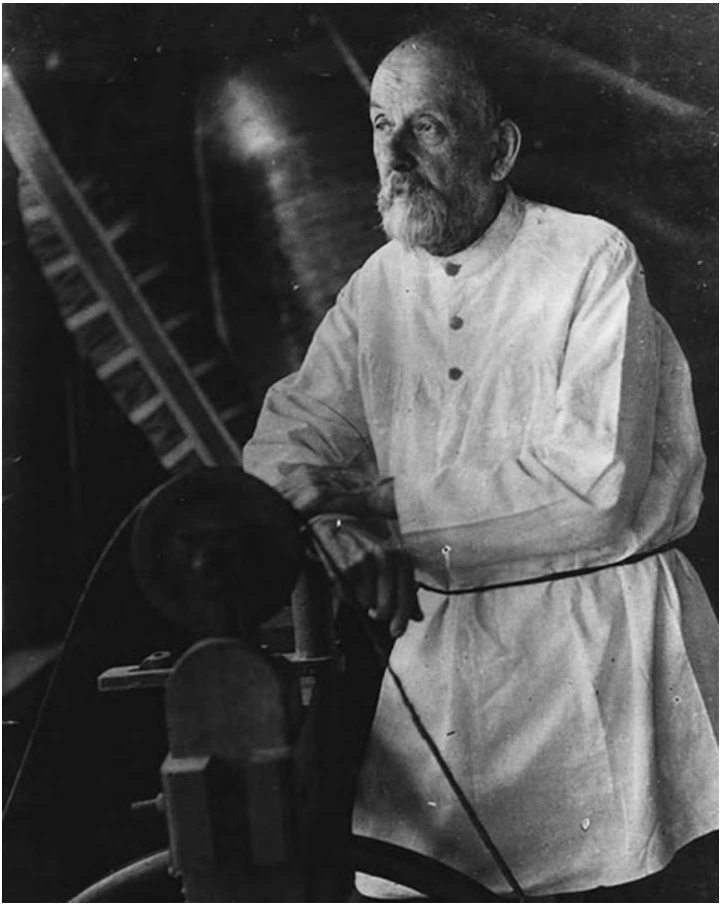


Figure 3.1: Konstantin Tsiolkovsky, the ''father of rocketry.''

Building such an unbelievably high, free-standing tower would be extremely difficult. In early 1962 the Convair Division of General Dynamics carried out a feasibility study on very high towers, for possible use in astronomy, high-altitude research, and communications, and for launching rockets above the dense part of the atmosphere. The researchers theorized that towers can be built up to an altitude of about 6 kilometers (4 miles) using steel, and up to an altitude of 10 kilometers (6 miles) if aluminum is used. That is comparable to the height of the tallest mountains, so there would be little point in trying to build such towers except that you could place them where they were needed. Nowadays there are novel construction materials, such as graphite composites, that could make much higher structures possible, but even these would be limited to several tens of kilometers in height.

Enormous towers would need to have very wide bases, looking somewhat like elongated pyramids, to be able to support their own weight. They would thus be of huge size and very expensive. Most importantly, they would still not be able to reach into space.

However, in 1960 another Russian engineer, Yuri Artsutanov, suggested a much better idea in the Young Person's Sunday supplement of the Russian newspaper *Pravda,* under the intriguing title "Into Space with the Help of an Electric Locomotive." Rather than building a tower from the ground up, he proposed to start with a satellite in geostationary orbit. From there, a cable could be lowered down to the Earth's surface while at the same time another one with a countermass could be deployed in the opposite direction to compensate for the first cable's mass. He estimated that the total length of cable required would be between 50 million and 60 million km (30,000 to 40,000 miles). This would ensure that during construction and thereafter, the satellite would always remain at the stationary point.

Although space travel was still very new and no cosmonaut had yet been put in orbit, Artsutanov correctly argued that in the future the construction of rockets was not going to change in principle and that these vehicles would always take huge amounts of propellant and effort to get into space. Moreover, he foresaw that in any rocket the passengers and cargo would be subjected to high acceleration loads. Artsutanov therefore considered a "cosmic cable way," with trains using electromagnetic fields gently climbing up, to be a much more elegant and efficient solution. After passing the equilibrium point (geostationary orbit), the trains would not even need to be powered as they would be driven on by the centrifugal force alone.

At the top of the cable Artsutanov imagined an entire city with greenhouses, observatories, solar power stations, workshops, propellant depots, and docking areas for interplanetary rockets (in reality it would be much better to locate most of this infrastructure at the lower geostationary point, where everything would be weightless). He argued that the rockets docked to the cable would already have orbital speed and thus would be much easier to launch from there than from Earth; not requiring heavy structures and high thrust levels, they would be more like ocean liners than like conventional launch vehicles. Artsutanov also considered the danger of damage to the cable by meteor impact; he proposed using a series of parallel and interconnected threads instead of one single tether.

However, although Artsutanov's concept does not require a tower reaching far into space, producing a cable over 50,000 km (31,000 miles) long would not be an easy task either. Artsutanov already warned that the cable would need to be made from especially strong materials that did not yet exist in 1960 (or even in our time, for that matter).

John McCarthy in the United States also had been thinking about a space elevator concept as early as the 1950s, but had dismissed the idea on the grounds that the cable required a tremendous tensile strength and such a material did not exist. As an alternative he invented the rotating Skyhook, a 10,000-km-long (6200-mile-long) rotating tether with its center of mass in a 5000 km (3100 mile) orbit. Each arm of the skyhook would thus touch down at the Earth's surface once every tether rotation, where a payload could be quickly attached to be flung into space. McCarthy can thus be considered to be the father of the momentum exchange tether.

In 1966, a team of American engineers led by John Isaacs of the Scripps Institute of Oceanography (the others involved were Allyn Vine, Hugh Bradner, and George Bachus) determined what type of material would be required to build a space elevator, assuming it would be a simple, straight cable without any variations in its cross section. It turned out that the strength required would be about twice that of the strongest materials existing at that time, such as graphite, quartz, and diamond.

However, the forces on a space elevator cable are not the same everywhere. The section of cable in geostationary orbit is in equilibrium, because its speed is just right so as not to fall back to Earth or to fly away; without the rest of the cable it would simply be in orbit as a satellite. The cable beyond it, going further into space, is effectively moving too fast for the altitude and tries to fly away. It is therefore pulling on the sections of cable below. The longer the piece of cable in the outward direction, the more mass is pulling and also the higher the difference in local orbital speed and cable velocity. Hence, looking back from the end of the tether, the closer to the geostationary point, the higher the loads on the cable. On the opposite side, the part going down from the geostationary point to Earth, there is a similar effect; in this case the cable is pulling down and trying to fall back to the surface. The tension force in the space elevator is thus highest at the geostationary point and diminishing in each direction.

Varying the cross section of the cable, so that the parts that require higher strength are thicker and the parts that need to handle lower forces can be made thinner and lighter, results in a better design that requires less extreme material properties. Such a tapered cross section of cable was briefly mentioned in the 1960 article of Artsutanov and was also considered by McCarthy and the Scripps Institute of Oceanography team, but the concept was properly studied for the first time by American scientist Jerome Pearson. Unaware of the earlier work, he independently conceived the idea of the space elevator in 1969 while working at NASA's Ames Research Center, and further developed it in the early 1970s when he was at the Air Force Research Laboratory in Ohio. His original design has relatively thin

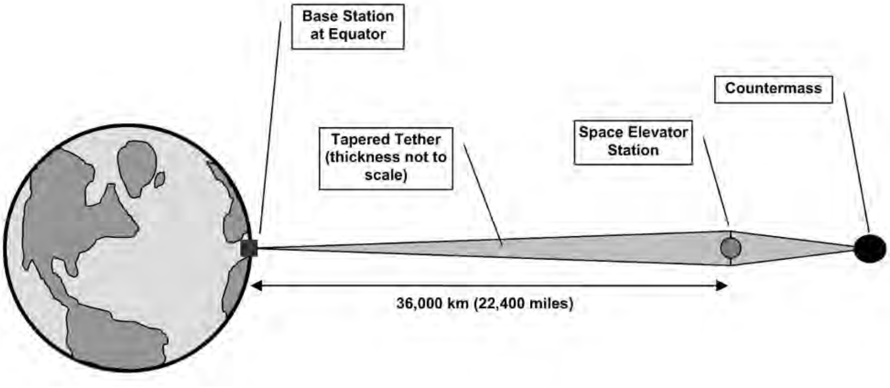


Figure 3.2: In the tapered space elevator concept, the thickness of the cable varies with the tension it needs to cope with (not drawn to scale).

connections close to Earth and the countermass, but grows in thickness toward the geostationary point, where the cross section reaches a maximum (the optimum taper profile is not linear). The ratio between the thickest and thinnest part is called the taper ratio (Fig. 3.2).

In theory, such a space elevator tether could be made of any material, but the less tension the cable material can handle, the higher the necessary taper ratio and thus the thicker the geostationary section. Using stainless steel and a cable diameter of only 10 centimeters (4 inches) on Earth, the tether would need to taper to a maximum thickness on the order of millions of millions of kilometers. However, with carbon nanotube materials currently under development, the taper ratio could be as low as 1 to 2—a maximum thickness only twice that of the minimum diameter.

Similar to Artsutanov, Pearson suggested unrolling a 144,000-km-long (90,000-mile-long) cable with a countermass to compensate for the mass of the lower section of cable reaching to Earth. Pearson included in his calculations disturbances such as the gravitational attraction of the Moon, the force of the wind on the lower end of the cable, and elevators moving up and down. Pearson published his ideas in the international journal *Acta Astronautica*, in which he described the use of the space elevator for launching payloads into space and to other planets without requiring rockets. He found that if all the mass of the needed material had to be brought from Earth, it would require no less than 24,000 Space Shuttle trips. However, part of the material could be transported up by small elevators riding a thin, minimum-strength tether lowered to the surface ahead of the real, heavier cable.

In the following decades the space elevator concept was developed further by a growing number of people. A strong sign that the idea was starting to be taken seriously was a workshop on space elevators organized by NASA's Marshall Space Flight Center in Huntsville, Alabama, in 1999, the results of which were published in 2000 in a report, "Space Elevators, an Advanced EarthSpace Infrastructure for the New Millennium."

In the meantime also other space tether applications were contemplated. In 1973 Mario Grossi of the Smithsonian Astrophysical Observatory suggested deploying a long wire from the Space Shuttle (a vehicle then still under development) to act as an antenna for extremely low frequency radio waves. This led in 1974 to the idea of Giuseppe Colombo of the Padua University in Italy to have the Shuttle "troll" a small satellite on the end of a long tether through the atmosphere. Colombo foresaw that this experiment could be used to study plasma physics and electricity generation in the upper atmosphere. The ideas of Grossi and Colombo led to the Tether Satellite System (TSS) that later flew on the Space Shuttle (see Space Shuttle Experiments in Chapter 4).

Fiction and Fascination

While engineers were defining the mathematical basis for the design of space tethers and space elevators, science-fiction writers and artists brought the new technology to the attention of a broader public.

A Russian volume of paintings by cosmonaut and artist Alexei Leonov and space artist Anatoly Sokolov published in 1967, *The Stars Are Awaiting Us*, contains a painting entitled "Space Elevator." The description accompanying the illustration states that it shows an "Earth–Satellite–Earth" elevator for freight and passengers that can operate without any rocket propulsion (Fig. 3.3).

In 1979 the famous science-fiction writer Arthur C. Clarke published his novel *The Fountains of Paradise*, which describes the development and construction of a space elevator in the 22nd century. Microscopically thin but ultrastrong "hyperfilaments" made from "continuous pseudo-one-dimensional diamond crystal" are used to construct the cable. The crystals are produced in space, where gravity does not impede their growth. The epilogue of the book describes the situation some 600 years after the construction of the first connection with space, when Earth is encircled by a giant ring—a wheel-shaped space station that is connected to the surface by several space elevators.

Clarke further addressed the space elevator concept in an article he published in *Advances in Earth Oriented Applied Space Technologies* in 1981, under the title "The Space Elevator: 'Thought Experiment,' or Key to the

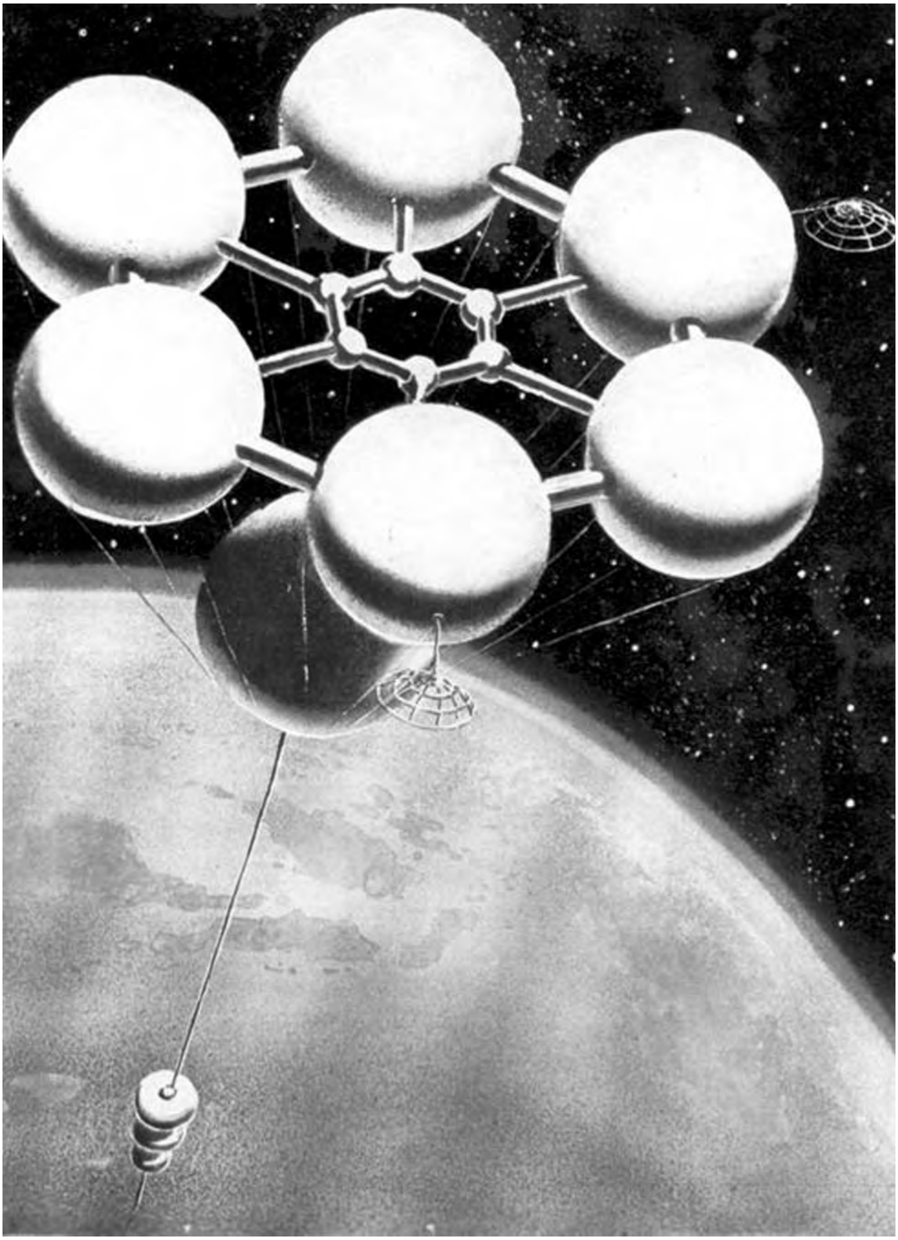


Figure 3.3: Artist's impression of a space elevator from the Russian 1967 book *The Stars Are Awaiting Us,* by Alexei Leonov and Anatoly Sokolov.

Universe?" In this article he explains the benefits of the Earth-circling ring structure that he discussed in *The Fountains of Paradise*:

> All the legions of geostationary satellites could be attached to it, and reached for servicing by an internal circular railroad. And it could serve as a launch platform for almost all missions, manned or unmanned, into deep space. It would be reached, of course, by space elevators, which would take the form of several spokes linking the ring city with the equator. The Earth would, in fact, now be the hub of a gigantic wheel, 85,000 kilometers in diameter. Passengers could move up and down the spokes, or around the rim, just as freely as they now move around the surface of the Earth. The distinction between Earth and space would be abolished, though the advantages of either could still be retained.

Nobody can accuse Clarke of not thinking big, but he soon found out that a Russian engineer by the name of Polyakov published a paper with the same idea almost simultaneously, and that Buckminster Fuller came up with the ring concept as early as 1951!

Space elevators also feature in Clarke's more recent works, such as *Firstborn*, a novel he wrote with Stephen Baxter and that was published shortly before his death in 2008. In this book three refugees escape Earth as stowaways onboard a cargo container ascending a space elevator ribbon. They disconnect the vehicle near the top of the cable, so that it is flung away into space for a rendezvous with an interplanetary spacecraft.

In the early 1990s, Clarke was asked when the space elevator would become a reality. He answered, "Probably about 50 years after everybody quits laughing." At the Space Elevator 2nd International Conference held in Santa Fe in 2003, he had become more optimistic, updating his estimate to "10 years after everybody stops laughing … and I think they have stopped laughing."

In the same year as Clarke's *The Fountains of Paradise* was published, Charles Sheffield published *The Web Between the Worlds*, which also describes the construction of a space elevator. It included a preface by Clarke explaining that his and Sheffield's book had been written independently and that the authors had not known about each other's book until recently!

The science-fiction writer with the most stories about space tethers was the late Robert L. Forward. Apart from the earlier mentioned *Camelot 30K* (1993) that describes a Space Catapult System, he wrote the books in the *Rocheworld* series that deal with the use of space tethers for orbiting and de-orbiting spacecraft (including *Flight of the Dragonfly*, published in 1984, retitled *Rocheworld* in 1990). Other books featuring tethers are *Dragon's Egg* (1980), *Starquake* (1985), *Martian Rainbow* (1991), and *Timemaster* (1992).

In 1993, Kim Stanley Robinson published *Red Mars*, in which a captured asteroid is mined by self-replicating Von Neumann nanotechnology machines (Von Neumann machines are named after physicist John von Neumann, who studied the theoretical concept of machines able to build copies of themselves, making it possible to "grow" huge factories out of a small number of machines). The machines multiply and then use the asteroid material to produce and lower a graphite cable 37,000 km (23,000 miles) down to the Martian surface. What is left of the asteroid remains in orbit, acting as a countermass for the space elevator. Elevator cars ride up and down the cable, taking several days to make the journey. When the 10-meter-thick (33-foot-thick) cable is later cut by saboteurs at its connection to the asteroid, it twists around Mars at 21,000 kilometers per hour, wreaking havoc on the planet's surface. A Martian space elevator is also sabotaged in Alistair Reynolds' *Chasm City* (2001) and a similar disaster, but on Earth, is described by Ben Bova in *Mercury* (2005).

In *Rainbow Mars* (1999), Larry Niven describes a space elevator that is literally a beanstalk, because it exists of a gigantic extraterrestrial tree that extends from Mars into space.

David Gerrold, in his novel *Jumping Off the Planet* (2000), has his protagonists visit a space elevator. Throughout the story technical details on the space elevator system are explained.

Many more science-fiction books featuring tethers, usually space elevators, have been published in recent years. Large tether systems are now also regularly featured in comics and cartoons. This is especially true in Japan, where stories about highly sophisticated and futuristic technology are very popular. In the "anime" (Japanese cartoon) series *Bubblegum Crisis Tokyo 2040*, for instance, a rotating skyhook plays a prominent role. In August 2006, the Japanese National Museum of Emerging Science and Technology in Tokyo started to show the animation movie *Space Elevator*, based on the Japanese ATA Space Elevator Project and directed by the project leader, Dr. Serkan Anilir. On television, an episode of the *Star Trek* series *Voyager* was devoted to a space elevator ("Rise," 1997). Even popular video games such as *Halo 3* feature space elevators. Although it is probably the most futuristic and most difficult to develop application, the space elevator now seems to be more firmly established in the popular media than any other space tether technology.

Early Experiments

4

Tethers have not yet been used as fully operational equipment, but various promising experiments have already been performed in space. Most were relatively unimportant add-ons to missions with some mass and volume to spare, but there have also been some for which the demonstration of one or more applications of tethers was a major objective.

Gemini 11

In the mid-1960s NASA flew the Gemini missions to develop and practice all the activities that were going to be needed for the subsequent Apollo missions to the Moon. The Gemini was a small, two-person capsule that was used for rendezvous and docking experiments, orbit change maneuvers, long-duration flights, and spacewalks in low Earth orbit. Tether experiments were performed on two of the Gemini missions—Gemini 11 and 12.

The Gemini 11 experiments marked the first time that a tether was flown in space, and the fact that the mission involved an astronaut crew made it especially exciting. The general plan was first to dock the Gemini to an earlier launched uncrewed Agena satellite, after which one of the astronauts would take a spacewalk and attach a tether between the Gemini and the Agena. Next, the astronauts would undock, and the two spacecraft would continue to orbit connected by the tether.

Without active control, the gravity-gradient effect would assert itself and ensure that one of the connected spacecraft would start to orbit below the other, with the tether perpendicular to the Earth's surface (as explained in the section Momentum Exchange in Chapter 1). Another possibility was to induce a rotation with Gemini's small rocket thruster attitude control system, making the two spacecraft rotate around their common center of mass. Not only was this to ensure that the tether would remain taut and the two spacecraft in a fixed position with respect to each other, it would also induce a level of artificial gravity. NASA decided to try both techniques (Fig. 4.1).

M. van Pelt, *Space Tethers and Space Elevators*, DOI: 10.1007/978-0-387-76556-3_4,

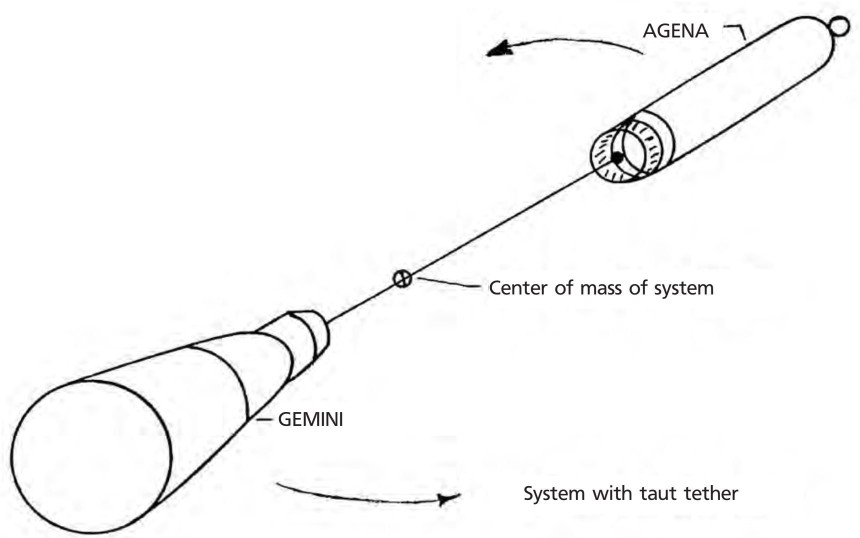


Figure 4.1: Original NASA drawing showing the principle of the artificial gravity experiment of the Gemini 11 mission. (Courtesy of NASA.)

The NASA Gemini flight operations performed an analysis that showed how the plan could work, then passed the data on to McDonnell, the company in charge of developing and building the Gemini vehicles. McDonnell's guidance and control group found that a reasonable amount of tension in the cable could be produced using a tether of length less than 50 meters (165 feet) and a spacecraft rotation rate of no more than 10 degrees per second. The tether was to be made of artificial nylon or Dacron fibers, so that it would be thin and lightweight yet strong enough to handle the pulling force between the Gemini and the Agena. Eventually a 36-meter (118-feet) Dacron line was selected.

With respect to safety, the only major question was how to release the Gemini from the Agena and the tether afterward. With the Agena attached, it would be hard to make the de-orbit maneuvers needed to bring the crew back to Earth. Moreover, reentering the atmosphere with the large mass of the Agena swinging at the end of a cable would be extremely dangerous. The solution was to fire a pyrotechnic charge that would eject the docking bar on which the tether would be attached. As a backup, a relatively weak link that could be snapped by a reasonably large separation velocity would be built into the tether.

Gemini 11 was launched on September 12, 1966, with astronaut Pete Conrad as command pilot and Richard Gordon as pilot. The crew's primary objective was to rendezvous and dock with the Gemini Agena target vehicle

(GATV) during the first orbit, which was successfully completed in just over 1½ hours after lift-off. Then it was time for Gordon to leave the Gemini capsule and move forward to the docked Agena and attach the tether, which was housed in the Agena target docking adapter, to the docking bar on his own Gemini capsule. He found this an extremely difficult job, because the Gemini and Agena turned out not have enough holding rails or foot restraints built into them. Gordon finally did manage to secure the cable, but only after a long and very tiring struggle.

For the tether experiment there were now two ways to proceed. For the first, the gravity-gradient test, the docked vehicle combination would assume a vertical position, with the Gemini on top. The crew would then undock and back their Gemini out of the Agena docking cone until the tether would be taut. The small difference in gravity acting on each spacecraft, due to their different altitudes, would ensure that the two would remain in a vertical position while circling Earth together. For the second test, the crew would fire the Gemini attitude control thrusters to induce a rotation of a safe 1 degree per second to the Gemini-Agena combination. That would make the two spacecraft cartwheel around their mutual center of mass, with the centripetal force keeping the line taut and the two vehicles safely apart.

The crew started with the gravity-gradient method. While carefully separating the two vehicles, the initial tension in the only partly deployed tether made both the Agena and the Gemini immediately move in unintended directions. However, Conrad quickly got the Gemini under control using the onboard attitude control thrusters. The Agena also had a set of thrusters that it automatically fired to adjust its own motion. Meanwhile, the two vehicles continued to back away from each other. Then, when about 15 meters had been deployed, the tether stuck, probably because it was blocked in the stowage container. With a burst of the Gemini's thrusters Conrad managed to jerk the cable free, but shortly after that the tether got caught again, this time on some Velcro that had been used to keep the cable wrapped up at the Agena's end. Moving the Gemini away from its vertical position with respect to the Agena, Conrad managed to peel the tether off the Velcro pad. However, that made the Agena lose its attitude stability again (Fig. 4.2).

Gemini 11 had encountered a typical problem in deploying a tether in space: every time the cable became taut, it jerked on both spacecraft and made them move toward each other. Moreover, on the Agena the tether was attached to the side of the docking port, so pulling on the cable made it oscillate from side to side. Likewise, on the Gemini the tether was connected above the spacecraft's nose, so that it disturbed the capsule's stability in

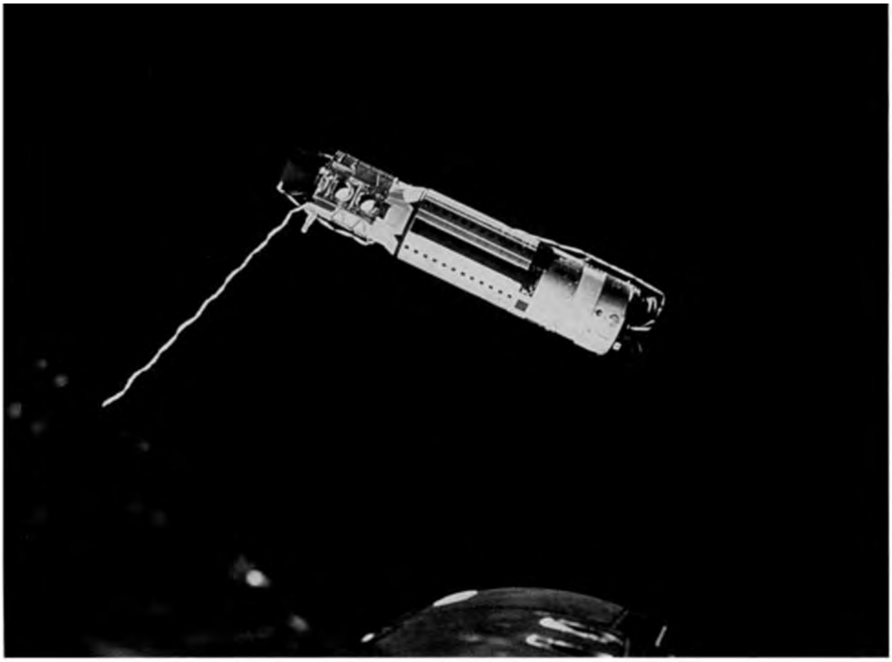


Figure 4.2: The Agena target vehicle and the tether connecting it to Gemini 11, as photographed by the astronauts. (Courtesy of NASA.)

pitch direction. Because of the complicated combined motions caused by the pull of the tether, it proved to be impossible to align the Gemini and Agena vertically with Earth and keep them in a stable position. The two crew members were therefore told to abandon their attempt at gravity-gradient stabilization and to proceed to the second mode.

For that, the crew first sent a signal to the Agena to turn off its automatic attitude control system, because otherwise it would refuse to rotate together with the tether. When Conrad then tried to start the rotation, he encountered another problem. “This tether’s doing something I never thought it would do. It’s like the Agena and I have a skip rope between us and it’s rotating and making a big loop,” he told Mission Control. Gordon then commanded the Agena to turn its attitude control back on, in the hope that that would help. But the disturbing motions persisted, causing him to report: “Man! Have we got a weird phenomenon going on here. This will take somebody a little time to figure out.” For 10 minutes the two crew members fought to straighten the tether. They finally managed, although both men never really understood what it was exactly they had done that stopped the cable’s weird behavior.

Now the slow cartwheel motion could be initiated. Conrad gently fired his thrusters, but nevertheless the tether soon had a big loop in it. The engineers on the ground told the crew to wait and see whether the centripetal force would pull the line straight. Soon the astronauts saw that this was indeed the case. Initially the vehicles at either end of the rope wigwagged a bit, but that movement also dampened out without any action from the crew. The astronauts managed to put the spacecraft combination in a steady, 38-degree-per-minute rotation as the spacecraft moved into the night side of its orbit. The movement was so stable that the astronauts were able to eat their evening meal undisturbed. Clearly, this mode of station keeping was working far better than the first one.

However, the rate of rotation was still about 40 percent less than originally planned, so when the capsule passed back into daylight Ground Control told Conrad to increase the spin rate. Somewhat reluctantly, the crew agreed to give it a try. Then Gordon suddenly shouted, "Oh, look at the slack! . . . It's going to jerk this thing all to heck." The acceleration had caused a sudden increase in the tension in the tether, which resulted in what Conrad called "this big sling shot effect." The crew members found themselves being seesawed in pitch direction by up to 60 degrees. Clearly unhappy with the whole maneuver, Conrad told Flight Director Clifford E. Charlesworth, "You just ruined a good thing." Nevertheless, Conrad managed to kill the oscillation movement of his vehicle with the use of the control thrusters. Surprisingly, the Agena's automatic control system managed to stabilize that spacecraft as well.

The rotation rate of the combination was now 55 degrees per minute, close to the intended 1 degree per second. With one full 360-degree rotation thus taking over 6 minutes, the resulting amount of artificial gravity was of course tiny and could not be felt by the crew. However, the level of gravity was noticeable, because when the crew members put a camera against the instrument panel and let it go, it slowly moved to the rear of the cockpit in a straight line.

After being tied to the Agena for 3 hours, the crew ended the tether experiments by jettisoning the spacecraft docking bar. Gravity-gradient stabilization had proven to be very difficult to realize, and the mission had not been able to successfully demonstrate it. The rotation method had not been easy to handle either, but Gemini 11 had at least proven that the concept worked.

Gemini 12

The gravity-gradient tether experiment was given another try on the next and final Gemini flight, which left the Florida launch pad on November 11,

1966. Onboard Gemini 12 were Command Pilot Jim Lovell (who later flew as commander of the ill-fated Apollo 13), and Pilot Edwin Aldrin (who later made the first landing on the moon with Neil Armstrong on the Apollo 11 mission).

As part of his spacewalk, Aldrin was to attach the tether onboard the docked Agena spacecraft to their Gemini 12 capsule. He and the engineers planning his "extra vehicular activity" (EVA) had learned a lot from the previous spacewalks, including the one of Richard Gordon during the previous Gemini mission. Additional and improved astronaut restraints had been added to the outside of the Gemini 12 spacecraft. Moreover, Aldrin had been training for his spacewalk in a swimming pool, putting just enough weight on his suit so that he would neither sink nor surface. This exercise technique turned out to be very realistic and extremely useful, and has become an essential step in all spacewalk preparations since then.

Aldrin's real spacewalk lasted no less than 2 hours and 20 minutes, but thanks to the thorough preparations it took him much less effort to perform the various tasks than it took the previous astronauts. Hand over hand he moved along a rail to the nose of the Agena docking adapter. Using his waist tether for restraint, he then tied the tether to Gemini 12's docking bar without experiencing any of the problems Gordon had encountered.

With the two spacecraft connected by the tether and Aldrin back safely inside, the attempt at gravity-gradient stabilization could begin. Lovell undocked from the Agena target vehicle and backed his spacecraft carefully away so that the Gemini, the tether, and the Agena formed a pole vertical to Earth. The tether deployed smoothly, with only a brief hang-up, but it would not become taut. Lovell tried to straighten the cable using the spacecraft thrusters, but was unsuccessful at this and also had difficulty controlling the Gemini's attitude. "Every time I wanted to pitch up or yaw, I would roll," he later reported. Nevertheless, even though the tether tended to remain slack and only tautened occasionally, according to the crew the vehicles did become stabilized as a result of the small difference in gravity between the spacecrafts' slightly different orbital altitudes. Both vehicles' attitude was upset occasionally, with Gemini 12 even wigwagging by about 300 degrees at one time. Tether dynamics were clearly more complicated and problematic than the theory had predicted. In its formal mission report, NASA stated that what caused the disturbances "is not completely understood, nor is the system behavior during and immediately following these excursions." After 4½ hours of tethered flight, the crew released the tether by jettisoning the docking bar (Fig. 4.3).

Gemini 11 had demonstrated that tether rotation could be used for station keeping and the generation of artificial gravity, and Gemini 12 had shown

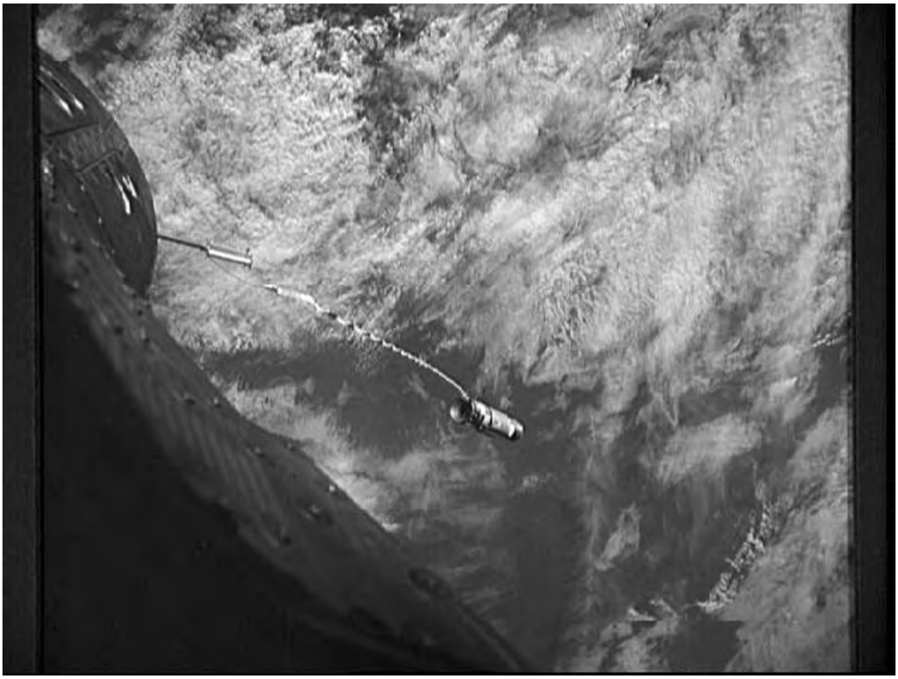


Figure 4.3: The Agena and tether seen from Gemini 12, in their gravity-gradient stabilized position. (Courtesy of NASA.)

some level of gravity-gradient stabilization. Both methods had revealed inherent difficulties, and more tests would clearly be necessary to completely master the complex dynamics involved. However, the Gemini program had ended, and no tethers were needed or flown during the subsequent Apollo program. It would be a long time before anybody would attempt the next tether experiment in space.

Suborbital

After the exciting Gemini experiments, it took no less than 14 years before anyone tried to fly tether technology in space again, and on a much more modest scale. Having been associated with the glory of pioneering crewed spaceflight, now it was back to obscurity for tether technology; the experiments of the early 1980s were all flown onboard suborbital sounding rockets.

The first two were launched in 1980 and 1981 as part of a joint program involving the Institute of Space and Astronautical Science (ISAS) in Japan and the Center for Atmospheric and Space Science of Utah State University in the United States. The project was named the Tethered Payload Experiment (TPE), and it used two Japanese rockets of different types: the Kappa 9M (flight K-9M-69) for the first mission and the S-520 (flight S-520-2) for the second. Both rockets were not built to go into orbit, but were just sufficiently powerful to reach very high altitudes and then fall back to Earth. During the unpowered flight upward and the subsequent fall, both in near-vacuum conditions, the experiments onboard would be experiencing microgravity just like on a satellite.

The use of sounding rockets made the experiments much simpler and cheaper than if a satellite had been used, and the equipment could also be retrieved. The most important reason for using sounding rockets, however, was that the TPEs had to be conducted in the ionosphere, the upper layer of the atmosphere were gases are ionized by solar radiation. The idea was to eject a stream of electrons from the rockets into the ionosphere. The negatively charged electron beam would influence the electrically charged atmospheric gases at high altitude, to a distance of 100 meters (330 feet) or more all around. A “daughter” payload connected by a tether to the main “mother” payload would be separated to make measurements inside and outside this charged bubble of gas. As the cable slowly deployed, the conditions at various distances from the origin of the electron beam would be recorded (Fig. 4.4).

The TPE-1 mission was launched with a Kappa 9M rocket on January 16, 1980, from the Japanese Kagoshima Space Center. When it reached an altitude of 150 km (93 miles), the electron beam was activated for 16 seconds. Immediately after, the motherdaughter parts of the rocket were separated with a spring system at a velocity of 0.5 meter per second (1.6 feet per second), unrolling the tether while drifting away. The plan had been to deploy 400 meters (1310 feet) of cable, but unfortunately the two rocket elements did not part by more than 38 meters (125 feet). Another disappointment was that the electron beam refused to work after the separation, due to a failure of the payload battery pack. The various passive sensors onboard the rocket nevertheless worked fine and collected a lot of data. The rocket reached a maximum altitude of 328 km (203 miles).

The next mission used a different sounding rocket, of the S-520 type, but the flight profile and payload instrumentation were very similar. TPE-2 left Kagoshima Space Center on January 29, 1981. At 200 km (124 miles) the beam was activated, and at 20 km (12 miles) higher the rocket split into its two parts. The spring system separating the two had been set to a higher force level, pushing the elements apart with twice the velocity of the previous mission. As a result, the tether now deployed to a distance of 65 meters (210

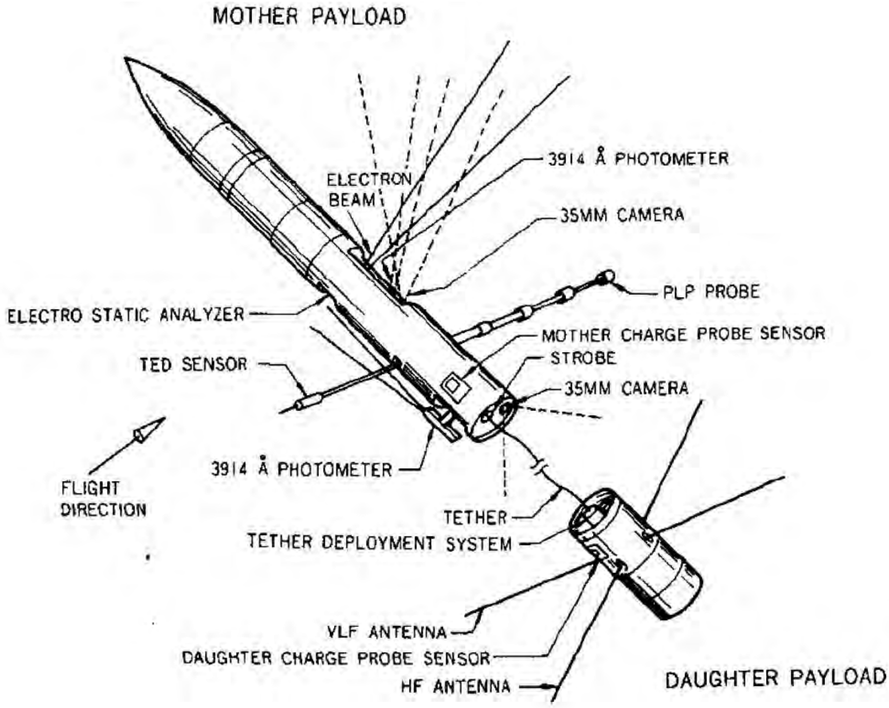


Figure 4.4: Configuration of the Tethered Payload Experiment. (Courtesy of Institute of Space and Astronautical Science [ISAS].)

feet)—further than before, but still far short of the 400 meters target. Also, the batteries failed once again, so that no active electron beam experiments could be performed after detachment of the daughter payload. The rocket reached an altitude of 322 km (200 miles).

Although on both TPE flights the payload parts did not separate as far as intended and the electron beam quit too soon, useful scientific data on the behavior of the ionosphere were obtained nevertheless. In addition, on the second mission the dynamics of the tether deployment had been recorded with a small CCD television camera. The pictures showed that the cable did not remain straight, but coiled up due to its own "springiness" and the lack of sufficient pulling force.

A third flight of the experiment was planned by ISAS and Utah State University, this time also involving Stanford University and the University of Michigan, and using an American Black Brant V rocket launched from the White Sands Missile Range in New Mexico. The new mission was named both TPE-3 and CHARGE-1, an acronym for Cooperative High Altitude Rocket Gun Experiment. The tether system for this mission was redesigned to minimize friction during deployment. Moreover, during separation small thrusters installed on the daughter payload would be activated every 40 seconds to generate a pull on the cable. The spring system was set to impart a velocity of 1.5 meters per second (5 feet per second), higher than during the previous two flights. The electrons released by the electron gun system would result in charging of the mother payload with respect to the daughter element. A metal wire was used as tether for this experiment, so that an electric current could flow between the two payloads and be measured.

CHARGE-1 was launched on August 8, 1983. At an altitude of 142 km (88 miles) the electron beam was put on, injecting electrons in a well-controlled configuration parallel to Earth's magnetic field lines. At 169 km (105 miles) the two rocket elements separated. As a result of the deployment system improvements, the tether now deployed to its full length of 418 meters (1370 feet). The ejection of electrons did result in a difference in electrical potential between the mother and daughter payload, creating a current flow through the tether. The cable was also found to act as a radio antenna due to this electrical current. However, the battery pack design was still flawed, and once again the electron beam stopped working after separation. The Black Brant reached an altitude of 218 km (136 miles) before falling back down. A mechanism was supposed to cut the wire once the rocket had descended below an altitude of 100 km (62 miles), but due to the strong aerodynamic drag the tether snapped just before the cutter was activated.

The experiment was launched again on December 14, 1985, and called CHARGE-2. The cable deployed to a length of 426 meters (1400 feet), the longest distance of all flights up to then. This time the electron gun and the instruments, which measured the characteristics of the plasma and the rise in electric potential of the mother payload with respect to the daughter element, worked perfectly throughout the flight. An onboard camera was also able to observe the trajectory of the electron beam.

The reaction control system thrusters on the daughter payload were activated for 3 seconds every 30 seconds. Not only did this result in a pull on the cable, but the released gas was also unexpectedly found to have an effect on the relative electrical charge of the two spacecraft elements. It reduced the electric potential of the mother payload, thereby resulting in an increase in the electrical current flowing from the daughter to the mother element through the conductive tether. The activation of the main reaction control system of the rocket itself was found to have a similar effect.

In 1992, CHARGE-2B flew similar equipment to that on CHARGE-2, as well as a separate, free-flying element. A Black Brant V rocket was again used for this flight. The mission was specifically meant to generate electromagnetic waves by modulating the electron beam in the frequency range of very low frequency (VLF) radio waves. Based on the experience with CHARGE-2, a system that slowly released cold gas was built in to prevent too high electrical charges from building up on the mother payload. The tether fully deployed once again to over 400 meters (1300 feet), and the experiments all worked as planned. The flight represented the last launch in the TPE/CHARGE series, but meanwhile two other projects with similar goals had already flown and a third was being planned.

On February 8, 1988, the U.S. Air Force Geophysics Laboratory launched the ECHO-7 payload onboard a Terrier–Black Brant V sounding rocket from the Poker Flat Research Range, near Fairbanks in Alaska. The mission was to study how an artificial electron beam propagates along magnetic field lines in space. The payload involved four different elements that were separated at high altitude and continued their flight on their own. One of the elements, called the MAIN payload, involved an electron beam gun and a tethered probe and was similar in concept to the payloads used on the TPE/CHARGE flights. Unfortunately, when the MAIN payload reached an altitude of 292 km (182 miles), close to its apogee, various pieces of onboard equipment failed due to a rapidly increasing electrical potential difference between the two payload elements; large electrical charges and sensitive electronic equipment do not combine very well.

Yet another sounding rocket experiment involving tethers was flown on January 30, 1989, onboard a Black Brant X three-stage rocket from the small launch site at Andøya in Norway. The mission was called OEDIPUS, an acronym for the imaginative name Observations of Electric-Field Distribution in the Ionospheric Plasma—A Unique Strategy. OEDIPUS-A was a joint program between the National Research Council of Canada and NASA, with the participation of the Communication Research Center of Ottawa, various Canadian universities, and the U.S. Air Force Phillips Laboratory. Also during this flight the payload consisted of two elements that separated using a spring and cold gas thruster system but remained connected to each other by a conductive tether. The cable was deployed over 958 meters (3140 feet), establishing a new record for tether length in space, and the rocket reached an altitude of 512 km (318 miles). The mission did not involve an electron gun, but only passive measurement instruments to study the ionosphere (Fig. 4.5).

The second flight of this experiment, OEDIPUS-C, took place on November 6, 1995, from the Poker Flat Research Range in Alaska using a Black Brant XII rocket. This time the rocket flew up to an altitude of 843 km (524 miles) and deployed 1174 meter (3852 feet) of tether.

The TPE, CHARGE, ECHO, and OEDIPUS suborbital flights provided interesting scientific data on the ionosphere, the interaction between

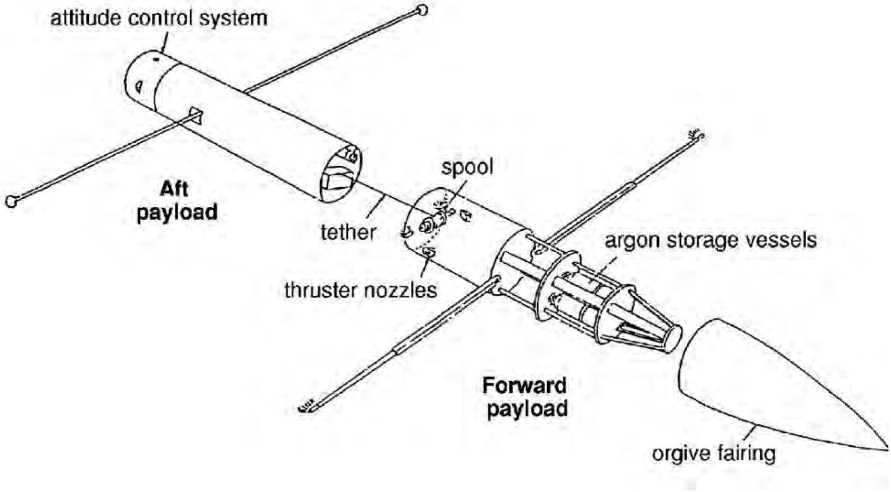


Figure 4.5: The configuration of the OEDIPUS experiment. (Courtesy of NASA.)

electron beams and ionospheric plasma, and the charge-mitigating effects of the release of gas. Moreover, important lessons were learned on the deployment of long tethers in vacuum and under microgravity conditions. These valuable experiences formed the basis for the next series of space tether experiments, conducted onboard the Space Shuttle. Space tethers were finally returning to Earth orbit.

Space Shuttle Experiments

One would have expected the next logical step, after the sounding rocket missions, would be to fly tethers on experimental, orbital satellites. The experiences with the Gemini flights and the various suborbital rockets showed that deploying tethers in space is not a straightforward thing, and that the dynamics involved were not yet fully understood.

However, the next tether mission was rather large, complicated, and daring, and involved the Space Shuttle. In July and August 1992, shuttle mission STS-46 flew the 518-kg (1142-pound) Tethered Satellite System (TSS), which consisted of a tether deployment and retrieval system, a small tethered satellite, and 22 km (13.7 miles) of conducting tether; 20 km (12.5 miles) of this would be deployed, and the rest would be kept as spare in case the tether would have to be unblocked by further unreeling if jammed on the deployer (Fig. 4.6).

The deployment/retrieval hardware was mounted on a standard Spacelab

Figure 4.6: The mission patch of STS-46 clearly shows the Tethered Satellite System deployed from the Orbiter's cargo bay. (Courtesy of NASA.)

pallet inside the shuttle orbiter Atlantis's voluminous cargo bay. It included a 12-meter (39-foot) extendible/retractable boom that would be raised out of the cargo bay to provide a safe clearance between the tethered satellite and the shuttle during the deployment and retrieval operations. An electric motor at the end of the boom would pull tether off the reel. The tether had a diameter of 2.54 millimeters (0.010 inch) and consisted of a braid of 10 copper wires wound around a Nomex string. This was encased in a Teflon sheath for electrical insulation, and then covered with a layer of braided Kevlar for strength, and an outer jacket of braided Nomex for protection against the aggressive atomic oxygen found in the uppermost layers of the atmosphere.

The spherical satellite was 1.6 meters (5.2 feet) in diameter and consisted of two parts: an upper hemisphere containing the scientific payload, and a lower hemisphere containing support systems such as electrical power equipment, communications equipment, and a data management subsystem. It also contained a cold gas propulsion subsystem that used nitrogen to control the attitude and movements of the satellite, and that would give the satellite an initial push away from the shuttle to start the deployment. Eight aluminum-alloy panels, covered with electrically conductive paint, formed the outer skin of the satellite. Doors in these panels provided access for servicing the batteries before launch, and windows were installed for charged particle instruments and attitude measurement sensors looking at the sun and Earth. Additional data-gathering instruments were mounted in the shuttle's cargo bay and its mid-deck area. Italy developed the satellite and provided five of the 10 scientific payloads needed for the experiment, while NASA was responsible for all other equipment and the overall mission.

The idea was to fly the shuttle with its cargo bay facing away from Earth, extend the deployment boom, and then deploy the tether and the small satellite at its end upward. Whether to release the probe up or down was no arbitrary choice, because the direction of motion of a wire through a magnetic field determines which way the electric current is going to flow through it. Due to the flight direction of the Space Shuttle and the direction of the magnetic field lines of Earth (from the South Pole to the North Pole), the flow of electrons through the tether was going to be downward. As the electron collector was built into the released satellite, and the plasma contactor emitting the electrons was positioned on the Space Shuttle, the probe had to be deployed upward. Once separated by some distance with help of the nitrogen thrusters, the small difference in gravity at the location of the shuttle and the satellite (the gravity gradient) would cause the two to be pulled apart and continue the deployment.

The gravity-gradient force grows in strength as the distance between the spacecraft increases, so the deployment of the satellite would begin extremely slowly, but then pick up speed to peak at about 6 km per hour (4 miles per hour) 1½ hours after undocking from the shuttle. At this point the satellite would be slightly less than 1½ km (1 mile) away from Atlantis and at a 40-degree angle behind the shuttle. The rate of deployment would then be slowed down briefly, reducing this angle to 5 degrees and putting the satellite almost directly overhead of Atlantis by the time that about 5 km (3 miles) of tether would be unwound. At 6 km (3.7 miles) away from Atlantis, a one-quarter revolution per minute spin would be induced on the satellite by its control thrusters. The slow spin was needed for science operations with the satellite, enabling its sensors to have a good look around.

After this, the speed of deployment would be gradually increased, climbing to almost 8 km per hour (5 miles per hour) about 4 hours into the deployment and with the satellite at a distance of about 15 km (9 miles). The speed would then gradually decrease, with the satellite coming to a stop almost 5½ hours after undocking. It would then be almost 20 km (12.5 miles) away from Atlantis. Just prior to full deployment, the satellite's spin would be stopped briefly to measure tether dynamics, and then a seven-tenths of a revolution-per-minute spin would be imparted to it.

The fully deployed cable would then be dragged through Earth's magnetic field for 31 hours to explore the dynamics and electricity-generating capacity of the system. As described before (see Electrodynamic Tethers in Chapter 1), the generation of electricity in this way would also result in a braking force on the Space Shuttle, slowing it down. At the end of the experiment, the tether would be rolled in for retrieval of the satellite. The objectives of the TSS-1 experiment were to verify the performance of the TSS equipment, to study the electromagnetic interaction between the tether and the ambient space plasma, and to investigate the dynamical forces acting upon a tethered satellite.

Things did not go according to plan, however. The first attempt to deploy the TSS tether and satellite was soon aborted by the crew members when they saw that the satellite was moving excessively side to side. They then quickly checked the status of the tether reel and the cold gas control thrusters, and made a second attempt a minute later. Initially the deployment was now going smoothly, but a minute later, when unreeled to a length of 179 meters (587 feet), the tether became blocked. It was thought that the cable had gotten stuck on the reel, maybe due to buried winding, so the tether was reeled in some 5 meters (16 feet) and then deployed at a somewhat higher rate. Unfortunately, at a length of 256 meters (827 feet) the satellite stopped once again (Fig. 4.7).

After some investigations, deployment activities were resumed about 1½ hours later. The cable was only reeled out about a meter further before the system stalled again. It was then decided to call it a day, power down the satellite to survival levels (to prevent draining the batteries), and give the crew a rest. Thirteen hours later the satellite was reeled in to a tether length of 224 meters (733 feet), where the cable jammed once again. This time the astronauts were unable to move the tether in either direction.

With the tether completely stuck, not only could the experiment not continue, but the crew would also be unable to retrieve the satellite and fly it back to Earth. A plan was developed to determine the location of the jam,

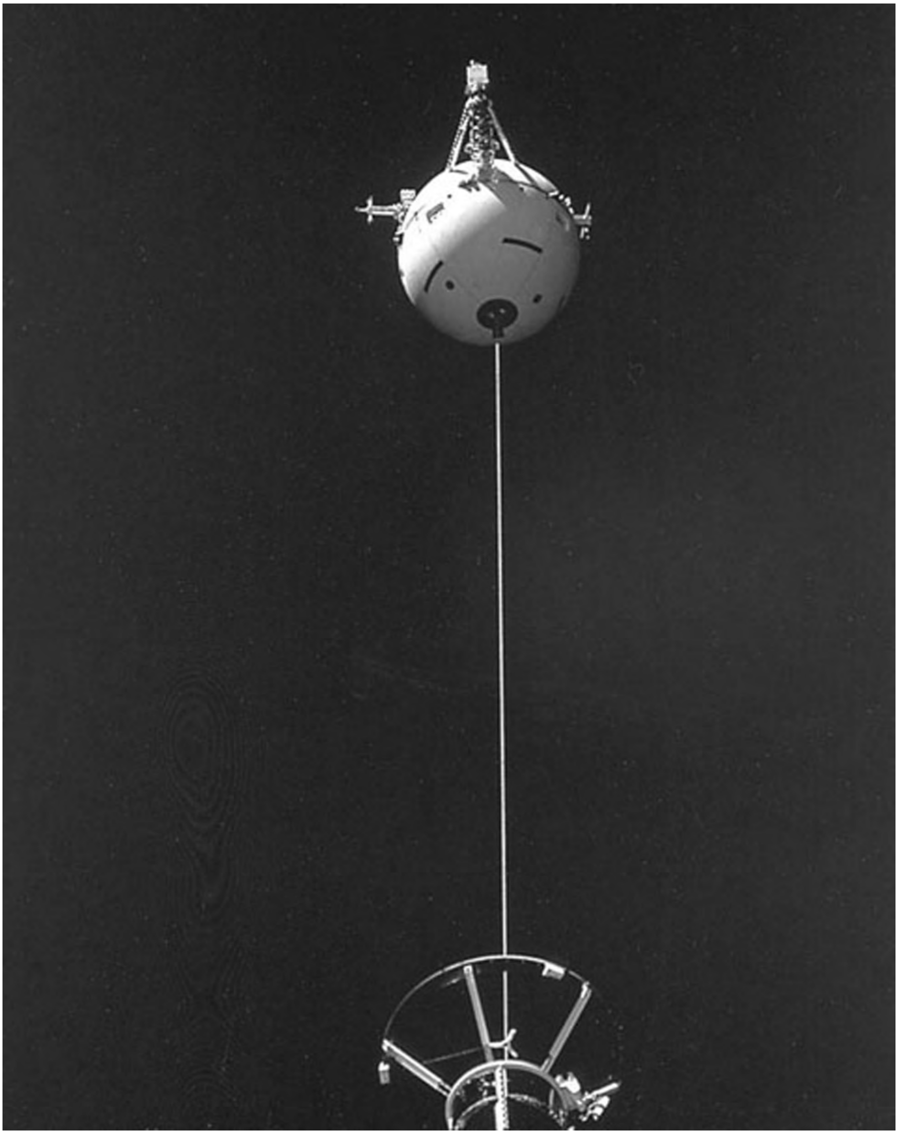


Figure 4.7: The TSS satellite and tether being deployed from the Space Shuttle. (Courtesy of NASA.)

which was believed to be in the upper or the lower tether control mechanism. It was decided that if the block could be cleared, the satellite would be brought back in and secured in the cargo bay.

Seven hours later the deployment boom was retracted a short distance, allowing the crew to visually check for a tether block inside the boom structure. The crew did not see anything amiss there, which meant that the jam had to be somewhere at the upper tether control mechanism located below the structure. The boom was then reextended with the reel brakes engaged, effectively stretching the tether in the hope of clearing it from any slack. The plan worked, and the satellite was successfully retrieved and docked at the top of the boom. The boom was then retracted, stowing the TSS system for the flight back to Earth. Clearly a redesign of the TSS was needed.

The system got another flight opportunity during shuttle mission STS-75 with orbiter Columbia, which was launched in February 1996. On February 25, the satellite of TSS-R (R stands for reflight) was deployed. This time mile after mile of tether was rolled off without any problems, and the electrical current through the tether grew with the increasing length, just as predicted. Then, close to full deployment with 19.7 km (12.2 miles) of tether unreeled, the tether suddenly broke near the deployment mechanism. The free end with the attached satellite, which was still in radio contact with the shuttle, snaked away into space.

Finding out what had happened was not easy. Recorded measurements of the stress in the cable showed that it was as predicted and within limits when the tether broke; the break was thus not caused by a too heavy pull. Fortunately, the shuttle returned the remaining length of tether back to Earth, so that it could be thoroughly investigated. When the frayed end was examined, it was discovered that an electric current had melted the tether. Tests in vacuum chambers on Earth showed what had probably happened. One very likely cause of the problem was found to be the innermost core of the tether, around which the copper wires were braided. This core was made of Nomex, a porous nylon material. During the manufacturing process, small bubbles of air at normal atmospheric pressure got trapped inside the material. In the vacuum of space, this air may have leaked out and been converted into a plasma by the high voltage of about 3500 volts in the tether (similar to what happens when you turn on a neon light tube). A plasma consists of negatively charged free electrons and the remains of the atoms from which these electrons were ripped away by the voltage, which are thus positively charged. Moreover, the density of the plasma would have been relatively high, turning it into a very good electrical conductor. Plasma bubbling away through tiny pinholes in the insulation layer could thus have resulted in an electrical current going through the plasma rather than the copper wires.

Another cause of an electrical arc on the tether could have been a breach in the insulation, caused by debris in or on the cable damaging the tether when it was wound onto the reel before flight. Later investigations did find various contaminating particles inside the tether as well as in the deployer mechanism.

The current flowing through the electric arc had a strength of about 1 ampere, enough to burn away most of the Kevlar at the location of the break. As a result, the tether lost strength and broke due to a pulling force between the satellite and the shuttle orbiter.

Although the experiment is often seen as an expensive failure, much scientific data had already been collected by the time the tether broke. Also, unlike during the first TSS flight, the deployment had been nearly completed without difficulty. All experiments on the satellite and the Space Shuttle worked and recorded data, and the electron guns used to eject the tether current back into the ionosphere from the orbiter worked well. Data was collected on the charged particle environment of Columbia's cargo bay, as well as on the effects of the shuttle thruster firings and water dumps on the tether and satellite. The experiment has led to important improvements in our understanding of tether dynamics.

The free-flying tether, reflecting light from the Sun, was visible from Earth. Many pictures were made, some clearly showing the satellite as a point of light at one end of the cable. Most observers reported that the tether seemed to be hanging below the satellite in a roughly vertical position, indicating that the tether had automatically achieved a gravity-gradient stabilized attitude (Fig. 4.8).

The experiment also inadvertently demonstrated the momentum transfer principle: when the tether severed, both the satellite and the shuttle moved into new, elliptical orbits. The change in the shuttle's orbit, however, was tiny due to the small mass of the satellite (68 kg [150 pounds]) in comparison to that of the shuttle orbiter Columbia (119,000 kg [262,000 pounds]).

Satellite Experiments

A relatively cheap way of conducting experiments in space is to put them on the upper stage of a rocket used to launch other satellites into orbit. An upper stage needs to achieve orbital velocity to deliver its cargo, so after deploying the payload satellites it is carrying into space, the stage itself becomes an independent and passive "satellite" (in fact, when people thought they were seeing tiny Sputnik-1 fly across the night sky in 1957, they were actually looking at the much larger upper stage of its launch rocket that went into orbit with it). If the mass of the cargo satellites is less than the maximum capability of the launcher, small experiments can be attached to the upper stage and flown along at often very little cost.

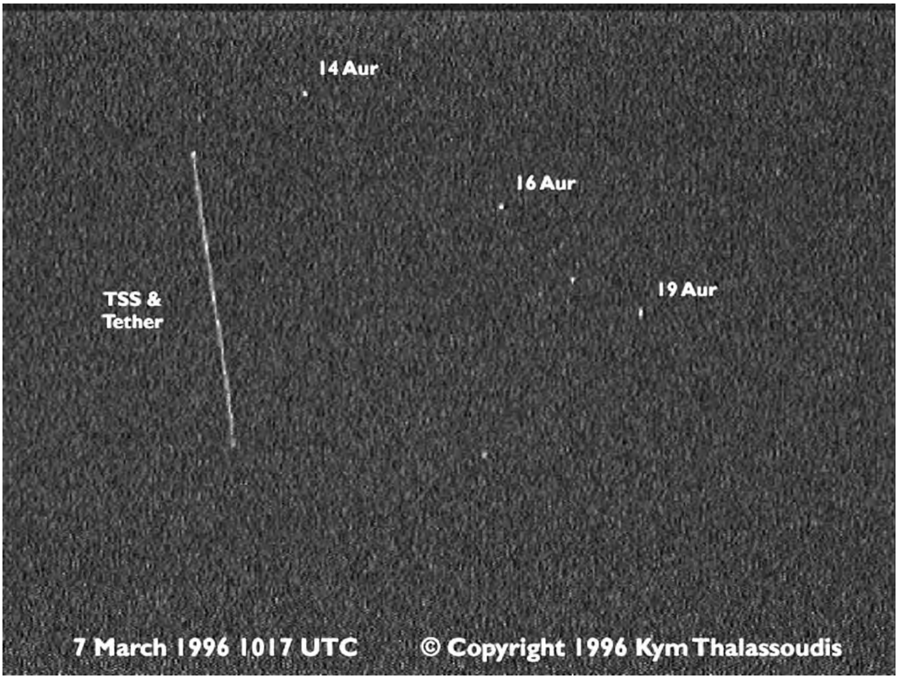


Figure 4.8: The severed TSS tether and satellite photographed from Earth, with several reference stars nearby. (Courtesy of Kym Thalassoudis.)

Several tether experiments involved putting equipment on upper stages and deploying tethers after delivery of the rocket's main cargo into orbit (so that they would not pose a risk to the expensive primary cargo). The first of these was SEDS-1, an acronym for Small Expendable Deployer System. It consisted of a 33-cm-long (13-inch-long) deployer cylinder with rolled up tether attached to the rocket stage, and a tiny "end-mass" 26-kg (57-pound) payload satellite. This satellite was a completely autonomous system that carried its own batteries, electronics, telemetry system, and sensors. It was connected to the rocket stage by a 20-km-long (12-mile-long) tether made of an especially strong, Kevlar-like material called Spectra-1000. SEDS-1 was developed and built by NASA's Marshall Space Flight Center, the Harvard–Smithsonian Center for Astrophysics, and Tether Applications of San Diego. The end mass satellite was built by NASA-Langley (Fig. 4.9).

SEDS-1 was launched from Cape Canaveral Air Force Station on March 29, 1993, attached to the second stage of a Delta II rocket with a GPS navigation satellite on board. An hour after launch, a spring ejected the end-mass satellite downward with a velocity of 1.6 meters per second (5.2 feet per second). This impulse carried the small probe far enough to allow gravity-

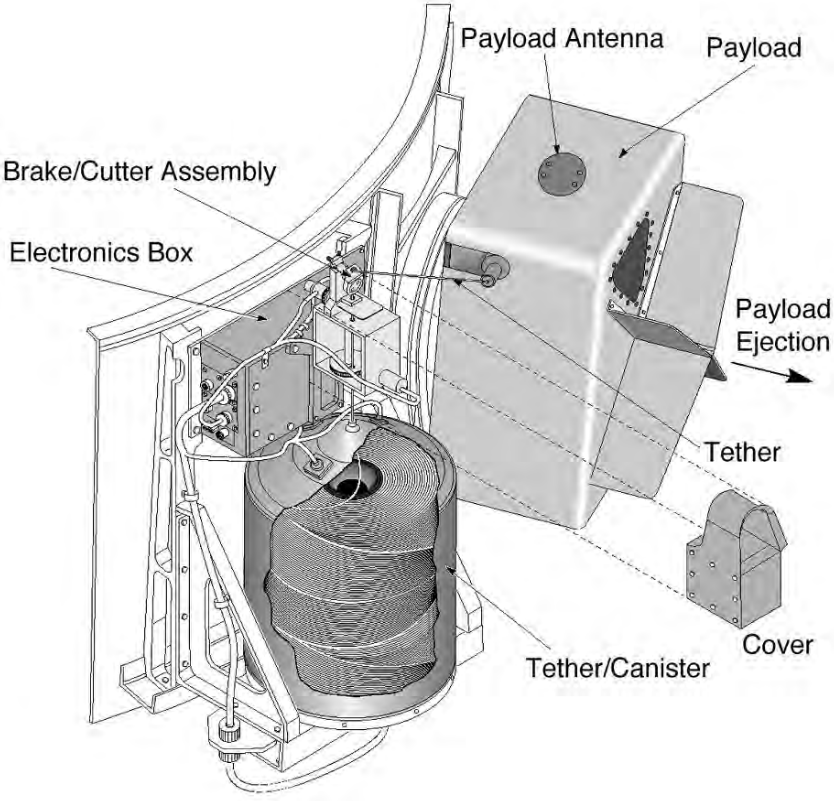


Figure 4.9: The SEDS system. (Courtesy of NASA.)

gradient effects to pull on and therefore deploy the tether faster and faster. When only 1 km (0.5 mile) of tether remained on the spool, active braking was applied. However, the braking was insufficient, so that when the tether was completely paid out the satellite was still flying away from the rocket stage. This resulted in a series of gentle "bungee" bounces at the end of deployment.

Because of the gravity gradient, the tether then swung to the vertical. One orbit after the start of deployment the tether was cut, slinging the satellite and tether onto a trajectory that made them reenter the atmosphere off the coast of Mexico. The reentry was accurate enough that prepositioned NASA observers were able to film the satellite and tether burning up high in the atmosphere. The last data collected from the satellite before reentry showed that the tension in the tether was rising as the aerodynamic drag began to blow the cable back, turning it into a kite tail.

SEDS-2 was launched on March 9, 1994, again onboard the second stage of a Delta II launching a GPS satellite. This time the tether and end-mass satellite would not be cut loose, but left attached to the rocket stage to determine long-term tether stability and the risks of micrometeoroid cutting tethers in orbit. SEDS-2 had an improved braking system that applied braking force as a function of the measured speed of the unrolling tether, and also started braking earlier than on SEDS-1. This was to ensure that the satellite stopped flying out just when the whole tether was deployed and to prevent the bounces experienced during the previous mission. The so-called "feedback control" worked well and limited the residual swing after deployment to only 4 degrees.

The small satellite with its 19.7-km (12.2-mile) tether returned data for 10 hours until its battery died. After 3.7 days the single-strand tether suffered a cut, probably due to a hit from a micrometeoroid or piece of space junk. The loose end of the tether and the attached satellite reentered within hours, but 7.2 km (4.5 miles) of cable remained connected to the Delta stage and survived with no apparent further cuts until the whole assembly reentered on May 7, 1994. Before that, the thin tether turned out to be rather easy to spot with the naked eye when front-lit by the sun and viewed against a dark sky. Many videos were made, all showing that the tether remained stabilized near a vertical position with respect to Earth's surface, even after the cut. The SEDS-2 mission thus proved that a tether can be accurately deployed to a stable vertical position in orbit by feedback control and a relatively simple friction brake.

On June 26, 1993, NASA and Tether Applications Inc. launched the Plasma Motor Generator (PMG) experiment onboard the second stage of an Air Force Delta II rocket. The system consisted of a far-end package satellite connected to the spent Delta stage by 500 meters (1640 feet) of conducting tether, orbiting Earth in a vertical configuration. The mission was designed to demonstrate that such a configuration could be used either to generate an electric current between the ionosphere and a spacecraft, or as an orbit-boosting motor (as described in the section Electrodynamic Tethers in Chapter 1). The current going through the tether was shown to be completely reversible. In the passive mode a current ran down the tether, proving that the system was capable of generating electrical power. As this power generation meant that orbital energy was converted into electrical energy and thus that the orbital velocity was decreasing, it was also demonstrated that the system could be used for braking and thus potentially for de-orbiting a spacecraft. When instead a current was actively driven up the tether, the Lorentz forces were shown to speed up the spacecraft and thus that the system could be used as a boosting motor, raising the orbit's altitude by converting electrical energy into orbital energy. The experiment lasted 7 hours, until the spacecraft's batteries expired.

The SEDS series should have been continued with a new mission similar to PMG named ProSEDS, for Propulsive Small Expendable Deployer System. ProSEDS involved a 4.4-km (2.7-mile) ultra-thin bare-wire conducting tether connected to a 8.7-km-long (5.4-mile-long) nonconducting tether made of Spectra and Kevlar (a strong synthetic fiber also used for making bulletproof vests), to be deployed from a Delta II second stage. Sweeping through Earth's magnetic field, the tether would have generated an electrodynamic braking force that would have lowered the orbit of the rocket stage. It was expected that this would have made it reenter the atmosphere in 15 days instead of the usual 120 days after launch. ProSEDS should have flown in 2003. However, after the tragedy with Space Shuttle Columbia in February 2003, NASA scientists reevaluated the risk that several already-planned space missions posed to astronauts onboard the Space Shuttle and International Space Station. They decided that the danger of the long ProSEDS tether at some time colliding with the Space Station was too high, and canceled the mission (Fig. 4.10).

TiPS, an acronym for Tether Physics and Survivability, was a relatively simple experiment designed to study how a tether would behave in space

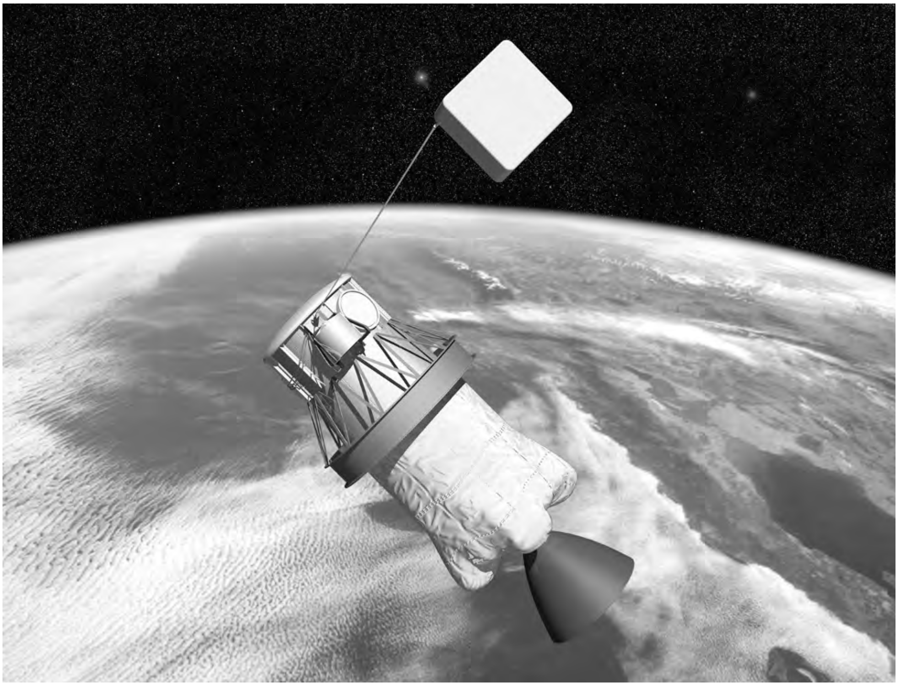


Figure 4.10: Artistic impression of what the ProSEDS experiment would have looked like in space. (Courtesy of NASA.)

over a long time, and how it would survive in an area with man-made orbital debris ("space junk") and natural micrometeoroids flying around at orbital velocities. The U.S. Naval Center for Space Technology designed, built and operated the experiment for the secretive National Reconnaissance Office (NRO). TiPs involved two satellites connected by a 4-km-long (2.5-mile-long) tether, and the whole assembly had a mass of 53 kg (120 pounds). The two end-mass satellites were named Ralph and Norton, after the characters Ralph Kramden and Ed Norton from the 1950s television show *The Honeymooners*. Ralph weighed 38 kg (83 pounds) and Norton 11 kg (24 pounds). The tether deployer and the radio transmitter were spare equipment from the SEDS-2 mission, donated by NASA. The tether braking system of SEDS-2 was not used, because it was not compatible with the thicker TiPs tether. This tether, made by AlliedSignal, consisted of two layers: an outer layer of Spectra-1000 braid for strength, and a core of acrylic yarn to expand the other braid out to a 2-mm (0.1-inch) diameter. It was hoped that this increased cross section would improve the tether's resistance to collisions with debris and small micrometeoroids (Fig. 4.11).

The TiPS payload was launched from Vandenberg Air Force Base on May 12, 1996, as a secondary payload connected to a host satellite onboard a Titan 4 rocket. It was placed in an almost perfectly circular orbit with an average altitude of 1022 km (635 miles) and an inclination of 63.4 degrees. The tether was completely deployed shortly after ejection of the TiPS system from the host satellite. Both TiPS satellites had reflectors on their exteriors to mirror back laser light aimed at them from Earth. By measuring how long it took the light to reach the satellites and return, and knowing the speed of light, it was possible to determine the precise orbit of the tethered system. Moreover, it was possible to tell the two satellites apart because they each reflected different light: Ralph's retro-reflectors were coated so that they reflected only green wavelengths, while the uncoated retro-reflectors on Norton returned both green and infrared wavelengths. Using this method, it was possible to determine the positions of the two satellites with respect to each other, and thus the attitude of the whole tether system.

For almost 1½ years the tether system was observed using satellite laser ranging, and the tether itself could be seen using large binoculars and small telescopes. TiPS laser tracking support was discontinued on October 15, 1997, at which time the tether was still intact. It finally broke in July 2006, more than 10 years after its launch. The data obtained from this mission have been used to validate analytical models and simulations for tethered spacecraft applications.

A follow-up to TiPS was the NRO's ATeX (Advanced Tether eXperiment), flown in combination with a parent spacecraft called STEX and launched

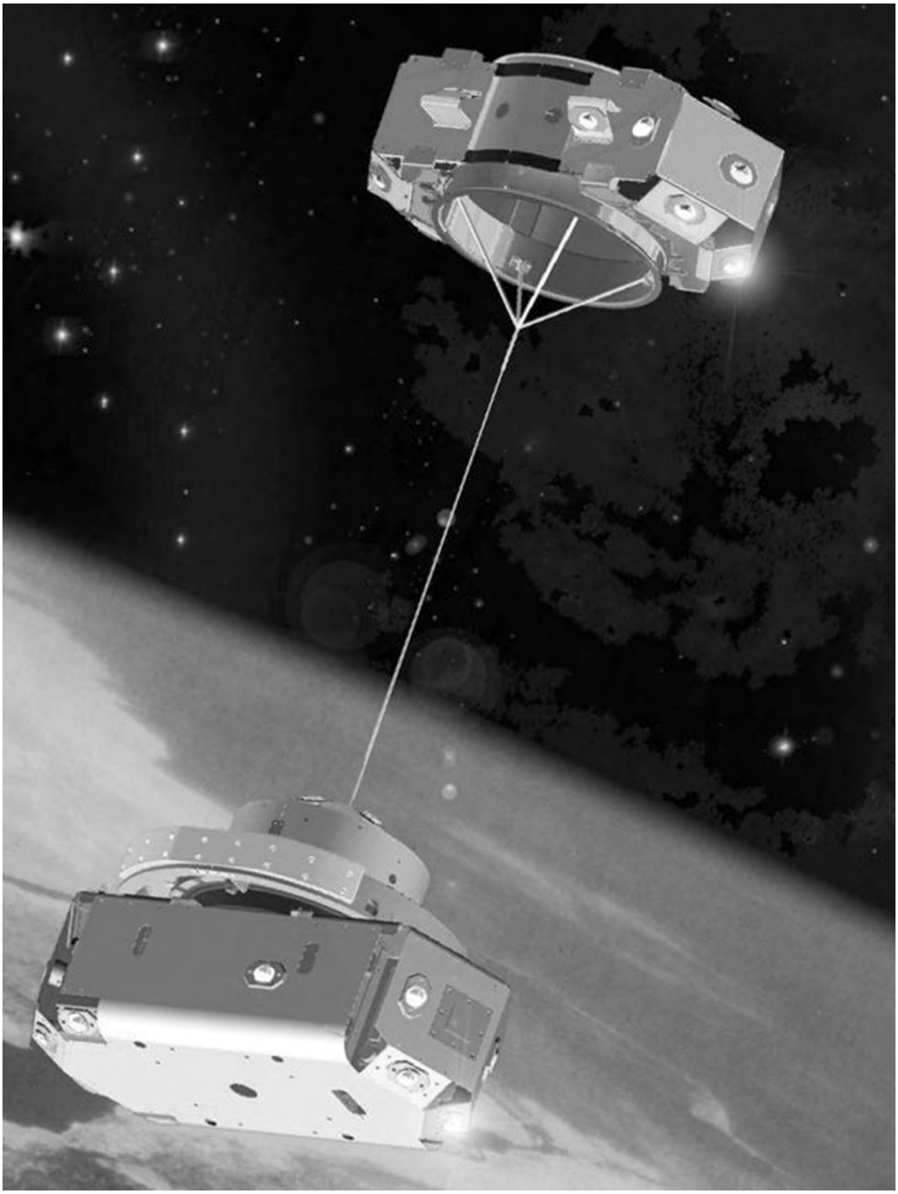


Figure 4.11: Artist's impression of the two satellites and tether of the TiPS experiment. (Courtesy of the U.S. Naval Research Laboratory.)

onboard a small Taurus rocket on October 3, 1998, from Vandenberg Air Force Base. ATeX comprised two end-mass satellites connected by a 6.2-km (3.9-mile) tether of polyethylene tape with three strands of Spectra material (to make the tether more resistant to the impacts of micrometeoroids and small scraps of space debris). This time the upper end mass was to be deployed while the lower end mass still remained attached to the STEX satellite. After a series of tether dynamics experiments in this configuration, the lower end mass was then also to be disconnected from STEX so that ATeX would become a free-flying system. Unfortunately, after only 18 minutes of deployment and with only 22 meters (72 feet) unrolled, sensors detected that the tether had moved away at an angle, far from its planned vertical position. This triggered an automatic safety system that jettisoned the whole ATeX system in order to protect the STEX parent satellite from colliding with the upper end mass and getting entangled in the tether.

The upper and lower ATeX end-mass satellites continued to orbit together, connected by only a short piece of tether as the system was not designed to further deploy the tether in the free-flying configuration. This rendered ATeX useless for any further tests. Later investigations pointed out that the tether's angle started to diverge from the vertical just when the spacecraft entered sunlight. The heat of the Sun made the tether expand, which may have disrupted the deployment and resulted in the tether going slack or the upper end mass satellite moving to the side. Thermal expansion of the tether had not been considered important for the deployment during the design of ATeX, and its impact was not realized until the analysis of the failure.

The first all-European tether spacecraft mission was YES, an acronym for Young Engineers' Satellite. This experiment was developed by Delta-Utec, a small Dutch space engineering company specialized in tether applications, in response to a unique opportunity brought about by a disaster.

On June 4, 1996, the first Ariane 5 rocket was launched. Even though it was the new launcher's qualification flight, confidence in a successful flight was so high that it carried a real, operational payload: the four satellites of the European Space Agency's (ESA) science mission, "Cluster." Unfortunately, 37 seconds after lift-off the rocket severely veered off its flight path. The high aerodynamic forces caused by an erroneous flight direction tore the vehicle apart, at which moment its automated destruct system activated to prevent the rocket from continuing any further. The first Ariane 5 blew up in a spectacular fountain of flaming and smoking debris. It was soon determined that an error in the guidance software had caused the failure; the Ariane 5 software had been based on that for the earlier Ariane 4 type launcher, but the flight path and in particular the acceleration profile of the new rocket was considerably different. No preflight tests of the software had ever been performed under simulated Ariane 5 flight conditions, so the error had remained undiscovered until the dramatic explosion.

An extra qualification flight of Ariane 5 was needed. This time it was decided not to risk a precious, operational payload again, but instead to launch an inactive dummy satellite. Wubbo Ockels, the first Dutch astronaut and an advocate for space tether applications, recognized that this flight provided a unique possibility to fly a small experimental tether payload. After the ESA showed initial interest, Ockels challenged Delta-Utec to come up with a viable plan. In one single week a proposal was worked out in detail and YES was born. Delta-Utec and a group of enthusiastic young engineers, students, and ESA professionals proposed building a small system consisting of two free-flying satellites: the YES satellite of 180 kg (400 pounds) and a smaller satellite of 12 kg (26 pounds) named TORI, for Tethered ORbit Insertable (and also named after a famous musician Tori Amos) connected to YES by a 35-km (22-mile) tether. To keep the tether light yet sufficiently robust, it was decided to use a double-strand cable, a so-called Carroll Caduceus tether (named after the inventor Joseph Carroll of Tether Applications, and after the caduceus, a short herald staff entwined by two snakes in the form of a double helix, carried by the Greek god Hermes).

The main objective of the experiment was to investigate tether deployment and dynamics in a geosynchronous transfer orbit (GTO; the elliptical transfer orbit in which a GEO satellite is initially launched), and to demonstrate tethered momentum transfer for future applications. The plan was proposed to ESA and soon accepted as a payload for Ariane 502 ("502" standing for the second flight of the Ariane 5). The ESA decided to combine YES with other experiments in a robust box dubbed "TEAMSAT," which would be integrated with the large dummy payload.

Unfortunately, the YES project hit a major snag. The Ariane 5 upper stage would put YES, TORI and the tether in an orbit that would expose the combination to only a small level of orbit degradation due to atmospheric drag. YES could thus stay in orbit for a very long time. The tiny but continuous pressure of sunlight on the relatively large surface area of the long cable could slow YES down and make it fall back to Earth, but the impact of that strongly depended on the direction of the Sun relative to the tether and its flight direction. This in turn strongly depended on the launch time of the rocket. As a result, the possible tether orbital lifetime was ranging from 2 months to tens of years. The risk that the YES tether would hit an expensive, operational satellite within a period of several months was deemed to be acceptable, but to have a rogue satellite with a long tether flying around for years would be too dangerous. Unfortunately, a change in the launch time of the Ariane led to a rather long expected orbital lifetime; the international Space Debris Committee determined that the collision risk the tether experiment posed to other spacecraft was too high, and therefore the tether was not allowed to be deployed. On October 30, 1997, YES was nevertheless flown on Ariane 502 and actually ejected from TEAMSAT, but the tether was not deployed and TORI remained mated to TEAMSAT. Sadly, without the tether, YES was unable to accomplish its main mission objectives.

A real application of a tether, although rather simple in nature, was a flight involving two miniature satellites, Picosat-1 and -2, developed by the Aerospace Corporation in the United States. Each had a mass of less than 250 grams (half a pound) and was only slightly larger than a deck of cards, making them the smallest active satellites flown up to then. They were launched on January 26, 2000, together with other small test satellites onboard a Minotaur rocket. The two were designed to perform basic tests on so-called MEMS (Micro Electro-Mechanical Systems) radiofrequency switches and were the first to demonstrate the principles of miniature satellites flying in formation and intersatellite communication via a local radio network. Each spacecraft also had a radio communications link with the ground.

The two picosats were connected by a 30-meter (100-foot) tether to ensure that they would stay close to each other (formation flying), which was necessary to test the micropower radio system that let the two satellites communicate with each other. In addition, the tether contained thin strands of gold wire that reflected radar signals, so that the satellite set could be tracked by the powerful radar systems of U.S. Space Command. They were deployed on February 6, 2000, and communications with the satellites were established 24 hours later. The spacecraft primary batteries ran out by February 10, 2000, which ended the successful mission. The same year the experiment was repeated with Picosat-7 and -8, again launched with a Minotaur on July 19.

A larger set of tethered Aerospace Corporation satellites were MEPSI-1A and -1B (for Micro Electro-Mechanical Systems-based PicoSat Inspector) launched with Space Shuttle mission STS-113 on December 2, 2002. The two cubic spacecraft had a mass of about 1 kg (2 pounds) each and were connected via a 15-meter (50-foot) tether to facilitate detection and tracking with ground-based radar. While the earlier tethered picosats did not have any means of propulsion, the MEPSI satellites carried a cold gas propulsion system. Its five thrusters of 0.1 newton thrust each (equivalent to the weight of a 10-gram [0.02-pound] mass in your hand) allowed some control of the spacecraft's attitude in space. The mission was part of a development that should result in a small autonomous satellite that can be carried on larger spacecraft and be used for remote inspection and servicing (presumably of its mothership as well as other satellites). Similar sets of MEPSI satellites were launched onboard STS-116 in December 2006 (MEPSI-2A and -2B), onboard STS-117 in June 2007 (MEPSI-3A and -3B), and with an Atlas rocket in March 2007 (MEPSI-4A and -4B) (Fig. 4.12).

Figure 4.12: MEPSI-1A and -1B, connected by a short tether, are released from the Space Shuttle on mission STS 113. (Courtesy of NASA.)

Another very small satellite with a tether was DTUsat-1, developed and built by students from the Technical University of Denmark. It was to deploy a 450-meter (1480-foot) copper wire tether for lowering the satellite's orbit through electrodynamic braking. DTUsat-1 was launched together with an array of other small satellites and a test model for a Russian Earth observation satellite onboard a Russian Rockot launcher on June 30, 2003. Unfortunately the mission had to be declared a failure when no radio contact could be established with the satellite after it had been put in orbit.

Japan initiated a new national tether experiment with the launch of the small CUTE-1.7 (Cubical Tokyo Tech Engineering Satellite"). The experimental satellite was launched on February 21, 2006, onboard an M-5 rocket, together with the ASTRO-F astronomy satellite that was the primary payload. CUTE-1.7 carried amateur radio equipment, utilized a handheld personal digital assistant as a low-cost onboard computer, and was to be used as a training tool for students at the Tokyo Institute of Technology. At the end of its mission, several months after launch, the 4-kg (8-pound) satellite would deploy a conductive electrodynamic tether of 90 meter (300 feet) for a de-orbit test.

The satellite separated correctly from the launch vehicle and communications with CUTE-1.7 were established soon after; telemetry reception reports from radio amateurs were received from all over Japan. However, on the evening of March 16 CUTE-1.7 stopped accepting commands from the ground, possibly due to radiation damage to the computer's command processing controller, and consequently control over the satellite was lost long before the start of the tether experiment.

American investigations into the dynamics and survivability of tethers in orbit were continued with the MAST experiment, for Multi-Application Survivable Tether, developed by Tethers Unlimited, Inc. (TUI) in collaboration with Stanford University. The MAST experiment consisted of three picosatellites, named "Ted," "Ralph," and "Gadget" (picosatellites are spacecraft with a mass less than 1 kg [2.2 pounds]). During launch the satellites were stacked, together occupying a volume of only about the size of a loaf of bread. Once in orbit, the satellites were to separate and Ted would deploy a 1000-meter-long (3300-foot-long) tether between it and the other satellites. Gadget was designed to then crawl slowly along the tether extended between Ted and Ralph, recording images of the cable to enable study of its behavior in space and the detection of any damage (Fig. 4.13).

The tether involved was not a simple cable, but a special multistrand "Hoytether," patented by TUI and developed to increase tether lifetime. Tethers in space are threatened by micrometeoroids, space debris, erosion by highly corrosive atomic oxygen in the upper atmosphere, and material-weakening ultraviolet light from the Sun. To lower the risk of a tether

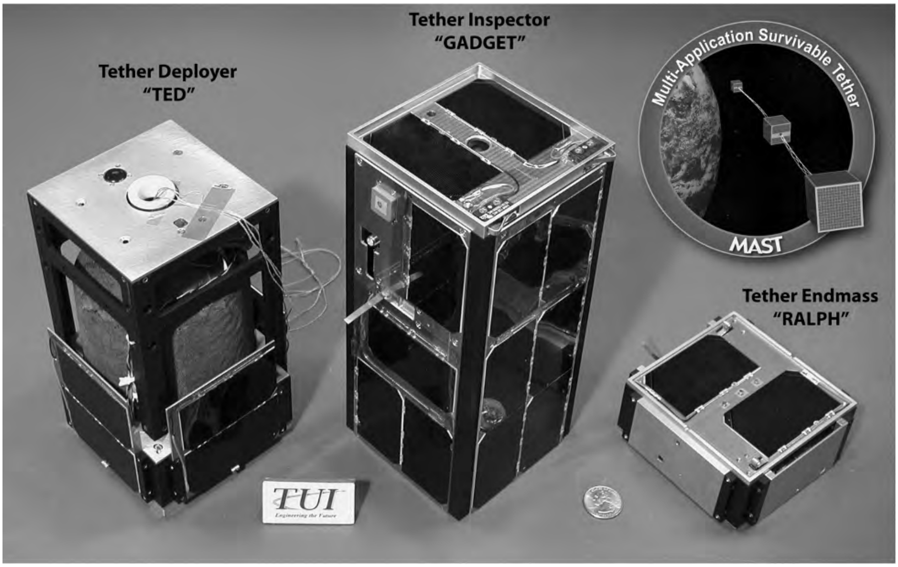


Figure 4.13: The three satellites and logo of the MAST experiment. (Courtesy of Tethers Unlimited, Inc.)

breaking due to any of these hazards, we can increase its diameter, but that quickly leads to a rather heavy and unwieldy cable. The Hoytether consists of a series of interlinked tethers instead of a single cable, and is therefore lightweight while still being less vulnerable; damage to one or more strands does not necessarily result in a break of the whole tether as long as the other strands remain intact.

MAST was launched on April 17, 2007, as a secondary payload on a Russian Dnepr, a former military ballistic missile converted to space launcher. The TUI engineers were successful in contacting Gadget, but the other satellites unfortunately remained silent. From the data obtained from Gadget, it was concluded that Ted did actually separate from Gadget and Ralph, but that a problem with the restraint system prevented it from ejecting smoothly and with sufficient speed. As a result, only a few meter of tether was deployed, too little for the planned experiment.

At the time of writing, the most recent tether mission is YES-2, a successor of the earlier described YES experiment. The Young Engineers' Satellite 2 was sponsored by ESA as part an experiment package that it flew on an uncrewed Russian Foton capsule for the Foton-M3 microgravity research mission. Delta-Utec, the Dutch contractor specializing in tether systems that was also responsible for the first YES, developed the experiment with the help of about 450 students from across Europe (Figs. 4.14 and 4.15).

Foton-M3 and YES-2 were launched by a Soyuz rocket from Baikonur, Kazakhstan, on September 14, 2007. On September 25, YES-2 deployed a small capsule, called Fotino, downward at the end of a 31.7-km-long (19.7-mile-long) tether. As Fotino dropped, it got closer to Earth and therefore its potential energy diminished (potential energy is the energy an object has by being at a certain altitude; moving it higher increases its energy, because when you let it fall it will achieve a greater speed than before and hit the ground harder). Since energy is conserved, the loss in potential energy resulted in a slight increase in kinetic energy and therefore velocity with respect to the Foton-M3 spacecraft. Orbital dynamics would thus cause the capsule to move in front of the mother spacecraft.

After rolling out the first 3.5 km (2.2 miles) of tether from the FLOYD deployer system, a pendulum-like swing was to be induced by bringing the deployment to a sudden stop. Subsequently, when the capsule would swing through the vertical with respect to Earth, it would be released from the MASS adapter at the end of the tether. The tether would then be cut at its origin, so that the Foton mission could continue without the long cable and Fotino support equipment at its end. After release, the Fotino capsule would not have sufficient velocity to stay in its now lower orbit (see Momentum Exchange in Chapter 1), and therefore reenter the atmosphere from an

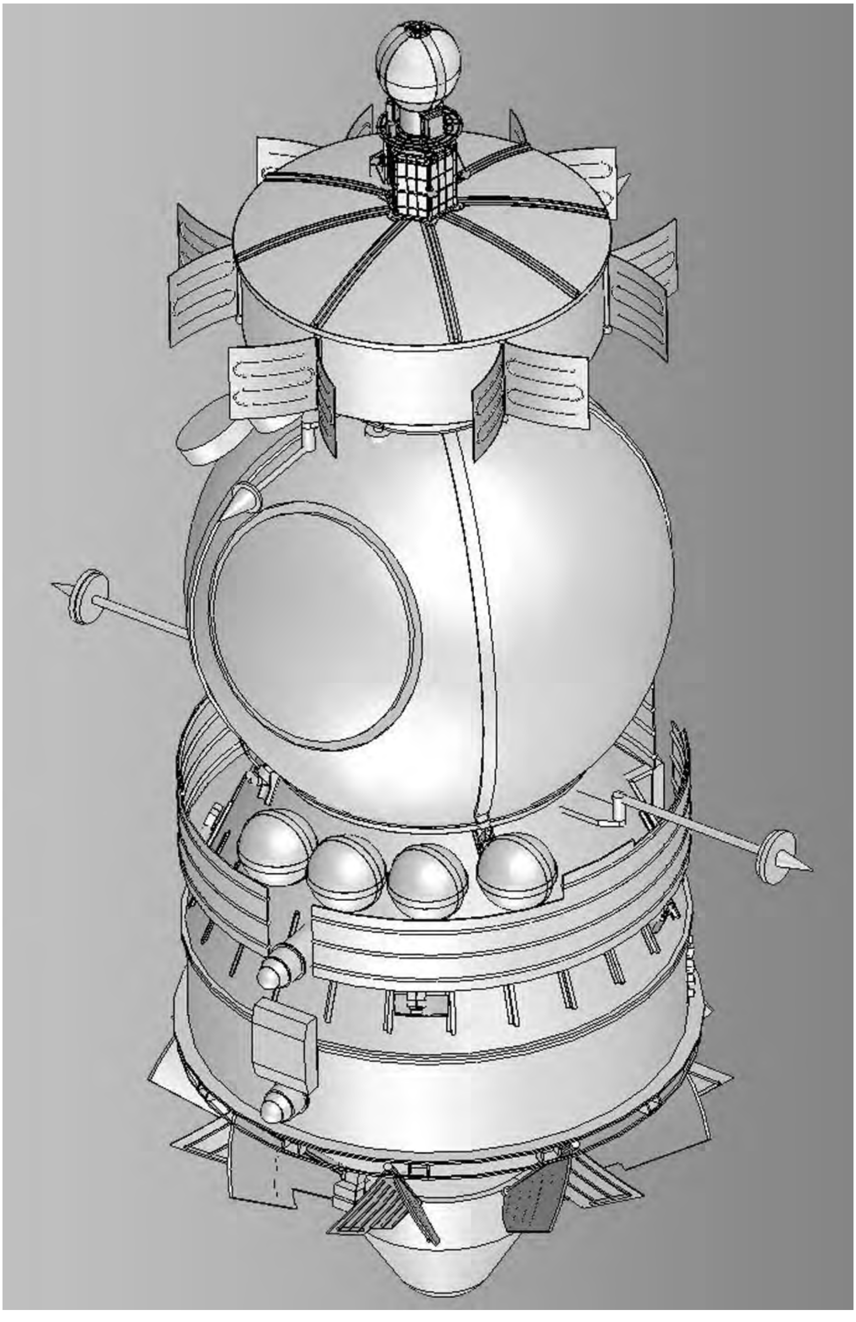


Figure 4.14: Drawing of the YES-2 equipment onboard the Foton spacecraft. YES-2 consists of the small ball-shaped capsule and deployer box on top. (Courtesy of ESA/ Dimitrios Lamprou.)

Figure 4.15: YES-2 being lowered onto the Foton-M3 spacecraft in preparation for launch. (Courtesy of ESA.)

altitude of about 250 km (160 miles). Protected by a heat shield, it was designed to survive the fiery fall through the atmosphere. At an altitude of 5 km (3 miles), a parachute would deploy to ensure a soft landing on the steppes of Kazakhstan (Fig. 4.16).

The ejection and the initial 3.5-km (2.2-mile) deployment went according to plan, but then the tether seemed to slow down. Initial data indicated that a total length of only 8.5 km (5.3 miles) was reached before the preprogrammed command released Fotino and cut the tether. However, a better look at the measurements several weeks later indicated that the whole 31.7 km (19.7 miles) of cable was actually reeled out (more than the planned 30 km, due to a failure of the braking control system). Accelerations measurements from the Foton spacecraft confirmed the successful deployment, and also showed that the Fotino had been released exactly when the tether swung through the vertical. The complete deployment makes the YES-2 cable the longest space tether ever deployed.

The U.S. Space Surveillance Network, which tracks satellites using powerful ground-based radar systems, reported that the Foton-M3 had gained 1.3 km (0.8 mile) in orbit altitude due to the tether deployment. Because the orbital energy remains the same and the center of mass of the system thus stays in the same orbit, lowering Fotino on its tether made the Foton capsule go up in a compensating reaction. When the tether was cut,

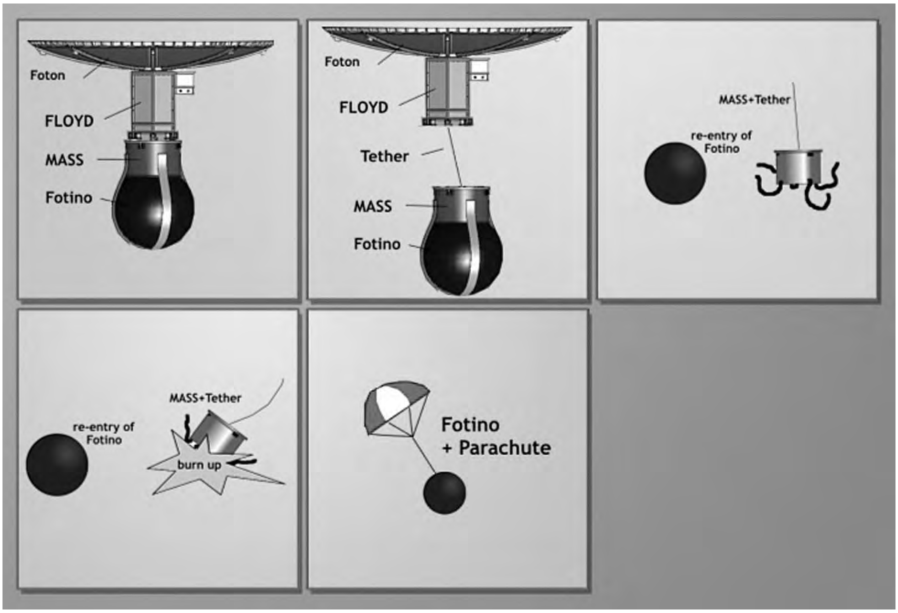


Figure 4.16: The main steps of the YES-2 experiment. (Courtesy of ESA/Marco Stelzer.)

the Foton on its own was suddenly flying too fast for its orbit and therefore entered a higher, elliptical orbit. The measured altitude gain of the Foton-M3 corresponded with what simulations showed would happen if 31.7 km (19.7 miles) of tether would be extended—another strong indication that the YES-2 tether had in fact been fully deployed.

The planned braking at the end of the deployment, to gently initiate the pendulum movement, unfortunately did not happen due to problems with the control system. As a result, the tether experienced quite a shock, which even produced sound waves that traveled back and forth through the cable. It also meant that Fotino did not exactly fly the planned reentry trajectory after release from the tether, although later analysis showed it should still have ended up in the dedicated target zone. The capsule had enough energy in its batteries to send out a radio signal for 3 days after landing, but that signal was never picked up. It is therefore not exactly clear what happened with Fotino. However, since the Space Surveillance Network was unable to detect the capsule in space, the YES-2 team believes it did enter the atmosphere right after its release from the tether. The capsule may have burned up in the atmosphere or its radio system may have been damaged during landing. Another possibility is that the partly burned heat-shield material has blocked the radio signals it was sending out after landing.

It thus appears that the YES-2 experiment was very nearly a complete success: the entire, record-breaking length of tether has been deployed, and Fotino seems to have been de-orbited using momentum exchange only. Plentiful data has been gathered on tether deployment, dynamics, and de-orbiting, which may lead to an operational way of returning capsules, for example from the International Space Station, without the use of any form of propulsion.

Still Learning

What have we learned from all these experiments? As we have seen, the results have been mixed. The unreeling of tethers in space has proven to be rather tricky and to require well-designed and tested deployment mechanisms; all deployments using passive reels have been successful, but there has been lots of trouble with powered reel systems. Even if successfully deployed, tethers can get cut by orbiting debris and meteoroids, or burned through by electric arcs.

Tether deployment is very hard to test on Earth, because we cannot simulate microgravity for sufficient lengths of time on the ground. Drop towers, in which experiments can free-fall and thus experience microgravity, offer only seconds of test time and cannot accommodate meters or kilometers of deployed tether. Most of the bridge leading from theoretical models to reality thus has to be crossed in space itself, where harsh conditions and the inaccessibility of the hardware after launch generally give experiments one shot only. When it does not work, it is back to the drawing board with, one hopes, some experimental data to improve the computer simulations and the design for the next try. With luck and perseverance, there may then be another chance to fly an experimental system several years later. Space tether technology is therefore a trial-by-error field. The fact that many tether missions have been performed with relatively low budgets and as payloads of secondary importance has not helped either.

Slowly, with more missions resulting in more experimental data and understanding, it is hoped we will be able to use space tethers as an operational technology in the near future, because, although the going is rough, the potential rewards are high, as we will see in the following chapters.

Into Earth Orbit and Beyond

5

Up to now, the use of space tethers has been experimental and mostly on a rather small scale. This chapter discusses the potential operational uses of tethers. Some proposed concepts apply what we have already seen but on a much grander scale, some combine multiple space tether types into one system, and some utilize them in completely new ways. There are plenty of ideas, some more feasible than others, but all fascinating and inspiring.

De-Orbiting

The potential tether application closest to Earth is for use in de-orbiting old satellites at the end of their useful lives, making them fall back into the atmosphere to burn up. That would lower the collision risk for operational spacecraft and prevent the generation of clouds of space debris frequently caused by inactive, deteriorating spacecraft.

Cleaning up the space around Earth is a serious issue. At the moment there are about 10,000 satellites and rocket upper stages zooming around our planet, of which only 4 percent consists of active spacecraft. Objects with a low perigee altitude remain in orbit for years, but ultimately get sufficiently slowed down by the tiny aerodynamic drag to fall back to Earth and burn up in the atmosphere. However, satellites in orbits above about an altitude of 700 km (450 miles) generally stay there for hundreds or even thousands of years. Because of the breakup of old equipment, collisions between objects, explosions caused by leftover propellant, and constant erosion by micrometeoroids, the amount of debris orbiting Earth is currently over a million identifiable pieces. With precise radar measurements from the ground, some 70,000 objects the size of postage stamps have been detected in orbits between altitudes of 850 and 1000 km (530 and 620 miles) alone—all bits of frozen nuclear reactor coolant leaking from a number of old Soviet satellites. In addition, more than 200 objects were thrown out of the Mir space station during its first 10 years of operation, most of them rubbish bags.

M. van Pelt, *Space Tethers and Space Elevators*, DOI: 10.1007/978-0-387-76556-3_5,

One spacecraft that created a huge amount of space debris was the upper stage of a Pegasus rocket launched in 1994, which blew up in 1996. The explosion generated a cloud of some 300,000 fragments bigger than 4 millimeters (0.16 inch) in diameter, in an instant doubling the space debris collision risk for the Hubble Space Telescope. In January 2007, the Chinese tested an anti-satellite (ASAT) weapon system by launching a missile against one of their own spacecraft. The rocket hit the old Fengyun-1C weather satellite and blew it into thousands of pieces. The U.S. military Space Surveillance Network identified more than 900 bits of debris over 10 centimeters (4 inches) in diameter. However, the total amount of debris resulting from the impact reaches into the tens of thousands of objects. NASA estimates that right after the test the number of debris fragments in orbit larger than 1 cm (0.4 inch) exceeded 35,000. "Any of these debris has the potential for seriously disrupting or terminating the mission of operational spacecraft in low Earth orbit (LEO). This satellite breakup represents the most prolific and serious fragmentation in the course of 50 years of space operations," said Nicholas Johnson, chief scientist for orbital debris at NASA's Johnson Space Center.

The added trouble of space debris is that it does not stay in the orbit of its original source, but drifts into different orbits due to explosions, collisions, aerodynamic drag, and irregularities in Earth's gravity field. What starts out as a small cloud of pieces of an exploded satellite thus soon covers the entire globe in a thick layer, like the skin of an orange. The cloud of debris created by the Chinese anti-satellite missile, for example, extends from less than 200 km (125 miles) to more than 3850 km (2390 miles) in altitude, encompassing all of LEO (Fig. 5.1).

A small piece of debris can create devastating impact energy because of the high orbital velocities involved: a tiny piece of 1 gram (0.04 ounce) moving in the opposite direction in LEO can hit a spacecraft as hard as a 1000-kg (2200-pound) car driving at 56 km/h (35 mph). In 1983, a tiny speck of space debris smashed into Space Shuttle Challenger's windshield and left a 4-mm (0.2-inch) crater. The debris was later identified as a chip of white paint, probably a remnant of a previous rocket launch. Between 1981 and 1996, shuttle windows sustained about 300 pits, and 55 panes were replaced, according to a 1997 National Research Council report.

The first collision of an active satellite with cataloged (i.e., known and radar-tracked) space debris occurred in 1996, when a piece of an exploded Ariane rocket upper stage tore off part of the gravity stabilization boom on a small French satellite called Cerise.

It is thus a good idea to de-orbit spent rocket upper stages and defunct satellites, especially before they start to break up into smaller pieces. This is

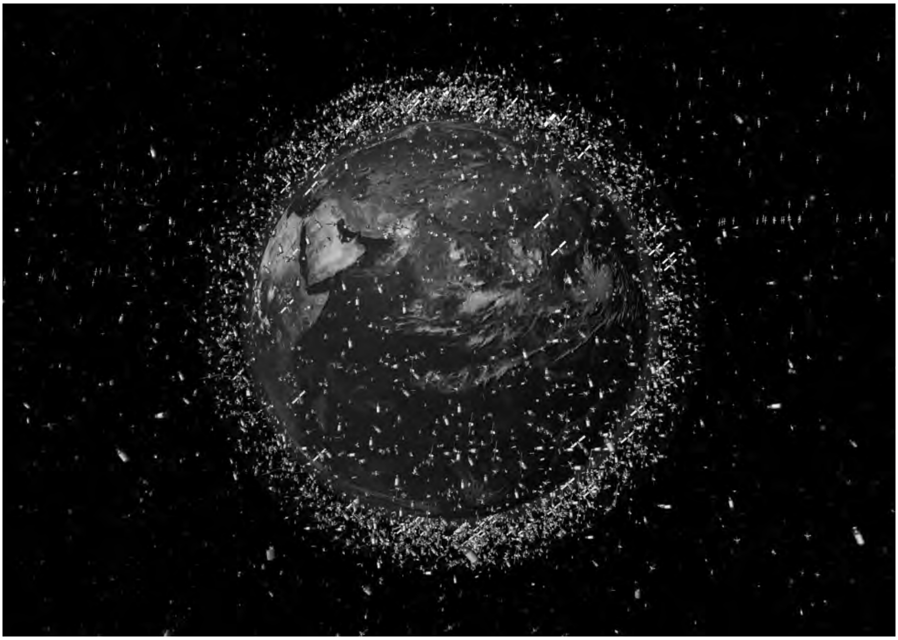


Figure 5.1: Artist's impression of active and inactive satellites and rocket stages in low Earth orbits (LEOs). Objects are shown at exaggerated sizes to make them visible at the scale shown, but their number and orbits are based on actual data. (Courtesy of ESA.)

occasionally done by slowing them down using onboard rocket propulsion. However, that requires propellant, which makes the spacecraft or stage heavier to launch or reduces the mass that can be allocated to useful payload. If no extra propellant is taken onboard, the attitude control propellant that needs to be reserved for the de-orbit burn shortens the satellite's useful lifetime. This is why active de-orbiting is currently applied only for spacecraft in relatively low orbits, where a modest push of a rocket motor can lower a satellite's orbit sufficiently for it to dip into the higher levels of the atmosphere. The increased aerodynamic drag will then slow it down further, until the spacecraft plunges down and burns up. Satellites orbiting more than a couple of hundreds of kilometers high, way above the atmosphere, would require too much propellant to be de-orbited.

Another problem with rocket propulsion de-orbiting is that it requires the satellite to be in good shape; if its attitude control system or onboard computer does not work well, the de-orbit burn may be executed in the wrong direction (resulting in a higher orbit and therefore increased time in space) or not happen at all.

Tethers Unlimited, Inc. (TUI), the small U.S. company specializing in advanced space technologies, has invented a system that could be used to de-orbit LEO satellites and rocket upper stages without rocket propulsion. Its Terminator Tether system is foreseen to be an independent package that is bolted onto a satellite. The only electrical interfaces with the satellite are those needed to monitor the health of the spacecraft it is connected to. As long as the satellite is operational, the device remains dormant, only waking up periodically to check the status of the spacecraft and listen for activation commands. When it is activated, either by a command from Earth or when it detects that its host has become defunct, it deploys a 5-km-long (3-mile-long) tether below the spacecraft. This tether is conductive, so that the ionospheric plasma and the geomagnetic field will induce currents running along the tether (as explained in the section Electrodynamic Tethers in Chapter 1). The resulting electrodynamic Lorentz force will slowly decelerate the spacecraft, lowering its orbit. Over a period of several weeks or months, the Terminator Tether could reduce the orbital altitude of the satellite or stage until aerodynamic drag and heating vaporize it in the upper atmosphere. The major advantage of this technique compared to other space propulsion systems is that, instead of propellant, it uses Earth's magnetic field as its reaction mass. The result is an overall smaller, lighter satellite that is less expensive to launch.

Because the system also needs to work in case the satellite is completely dead, the Terminator Tether package has to be highly autonomous. Apart from the tether, a deployer, an electron emission device (to keep the current going), and control electronics, it also incorporates its own radio receiver and a small battery kept charged by a small solar array. After deployment the current running through the tether can also be used to power the electronics and deployer mechanism of the tether system, keeping the initially required battery and solar array small and light. Besides the full-scale Terminator Tether, TUI has also designed a greatly simplified, miniaturized system, the Nanoterminator, which could be used on very small satellites.

A weakness of the concept is that while busy removing debris from space, the long Terminator Tether itself forms a collision risk for other spacecraft. Especially when arriving at lower orbits, the risk of the tether hitting an operational satellite may be higher than the original collision risk formed by the piece of debris it is trying to de-orbit. It may be better to discard the tether at low orbits, so that it is slowed down by the atmospheric drag more quickly (because its mass with respect to the drag force will be less than when attached to the defunct spacecraft). The actual piece of debris will then stay in orbit a bit longer, but the overall collision risk following this scheme is likely to be less than when keeping the tether attached until the end.

The earlier mentioned proSEDS experimental mission was intended to be a precursor for an operational Terminator Tether system, but unfortunately this project was canceled shortly before its planned launch. In the aftermath of the loss of Columbia, it became a victim of the more stringent safety rules for experiments in orbits close to that of the International Space Station (ISS).

An idea derived from the Terminator Tether concept is TUI's Remora Remover, which could be used to de-orbit spacecraft that are not equipped with a de-orbit system. This would involve an electrodynamic tether system onboard a small intercept vehicle. This small spacecraft could rendezvous with a spacecraft, then attach itself using a hooked net, harpoon, adhesive "sucker," or docking mechanism (hence the name Remora, which is a type of fish that attaches itself to larger fish and whales with a sucker-like organ). Once firmly connected, it would activate its onboard Terminator Tether system to remove the spacecraft from orbit. The Remora Remover could be used not only to de-orbit derelict satellites, but also to "kill" hostile or rogue spacecraft by bringing them down into the atmosphere.

Tether Applications, Inc., which was also involved in the SEDS-1 and Plasma Motor Generator (PMG) in-orbit tether experiments, has studied a somewhat similar concept on a research grant from NASA's Institute for Advanced Concepts (which ceased to exist in August 2007). Tether Applications' Debris Shepherd involves an intercept spacecraft with a long electrodynamic tether to de-orbit space junk. However, in this case the intercept vehicle would be able to generate electrical power using solar arrays. As we have also seen in the section Electrodynamic Tethers in Chapter 1, when using this power to run a current through a tether, a propulsive electromagnetic force can be created. Depending on the direction of the current, the Lorentz force can be used to either accelerate or decelerate a spacecraft, "pushing" it into a higher orbit or "pulling" it into a lower orbit. Such an electrodynamic propulsion tether can thus actively fly toward a target object, capture it, and then lower its orbit. Once the space debris object is delivered into a sufficiently low, short-lifetime orbit, the Debris Shepherd could undock and return to a higher orbit using its electrodynamic propulsion tether. The transported debris would relatively soon de-orbit under the influence of the upper atmosphere aerodynamic drag, while the Debris Shepherd would be free to start hunting for other large chunks of orbital debris to bring down.

The great benefit of the Debris Shepherd idea is that it is reusable. However, it needs its propulsive tether to be fully deployed during all its orbit changes, so control could be difficult (the NASA Institute for Advanced Concepts [NIAC] study proposed to use tethers about 10 km, or 6 miles, long). To avoid having to maneuver the long, flexible tether close to target objects and run the risk of entanglement or loss of control, Tether Applications thought of using detachable "Sheepdog" sub-spacecraft to inspect and capture the debris. Once having secured a good hold (bite) on the target, the Sheepdog would maneuver with its quarry and re-dock to the tether spacecraft.

The difficulty with designing systems like the Remora Remover or the Debris Shepherd is that they must be able to capture all kinds of spacecraft and rocket stages with all kinds of different configurations. Especially in the case of rogue spacecraft, there will be many unknowns about the target's shape, size, appendages, and so on, and finding a smooth surface to stick to or a sufficiently strong solar array boom to grab onto is likely to be very challenging. Additionally, it will be very difficult to make a firm connection with old satellites that are tumbling due to propellant leaks or attitude control problems.

Spacecraft Stabilization

As explained in Chapter 1 (see Momentum Exchange), the difference in gravity at different altitudes above Earth can be used to stabilize two tethered satellites into a vertical position. This was first demonstrated by the Gemini 12 mission and SEDS-2, although not without difficulty (see Chapter 4, sections Gemini 12 and Satellite Experiments). Such gravity-gradient stabilization does not necessarily require a tether; all that is needed is a spread of mass over a sufficient length—in other words, an elongated spacecraft shape, such as has already been employed by several small satellites that had long poles, called "gravity booms," attached instead of active onboard attitude control systems. Such poles create a gravity-gradient effect that is relatively weak but sufficient to stabilize small, low-mass satellites that do not have very accurate attitude control needs or pointing requirements.

However, for large satellites such poles need to be so long that they are hard to fit inside a launcher's nose cone, and they also make a spacecraft relatively heavy. For example, in the late 1960s NASA launched a series of experimental, geosynchronous applications technology satellites (ATSs), of which ATS-2, ATS-4, and ATS-5 were equipped with extendable booms to test gravity-gradient stabilization. These barrel-shaped ATS spacecraft each had a mass of about 320 kg (700 pounds) and needed 30-meter (100-feet) poles to maintain their attitude. Most modern operational satellites have much higher masses and would therefore need to have much longer and heavier booms that would be hard to launch even in a folded or telescoped configuration. For such satellites a deployable tether with a mass at the end could be used instead. Tethers can be rolled up for launch, resulting in compact payload packages that can fit inside the fairing of a rocket. Furthermore, long cables mean stronger gravity-gradient effects and thus more steady and robust stabilization.

The Smithsonian Astrophysical Observatory and the Italian space industry Alenia Spazio have studied the concept of using a long tether to stabilize a large space station for NASA. The ISS that is currently in orbit has a complicated configuration consisting of various modules and large solar arrays. Docking and undocking spacecraft, of which the Space Shuttle is the largest, have important and sudden effects on the position of the center of mass and the stabilization of the station. The ISS therefore requires a sophisticated attitude control system to ensure that the station always maintains the right attitude with respect to the Sun and Earth, primarily to guarantee the proper orientation of its solar arrays. If this control system suffered a malfunction, the station could quickly lose its correct orientation. This could make it impossible to point the solar arrays to the sun, resulting in an electrical energy shortage. An erratically moving station would also be very hard to dock to for any visiting spacecraft with vital supplies.

A deployable 6-km (3.7-mile) tether with a ballast mass of about 1400 kg (3100 pounds) could be reeled out to provide emergency attitude stabilization using gravity-gradient forces. The study listed as the main benefits of this system its simplicity, relatively low cost, and reusability; when the main attitude control system would be back in operation, the tether could be reeled in to be ready for use another time. The tether could also be permanently deployed to alleviate the requirements for the other attitude control system elements. The attitude tether stabilizer was not implemented on the ISS, which now has an attitude control system that consists of large gyroscopic wheels and a backup system with reaction control thrusters. The risk that an uncontrolled cable could wrap itself around the station and hinder the function of vital equipment (such as solar arrays and docking ports) has probably played an important role in the decision not to implement a tether system on the ISS.

Atmospheric Research

As described in Chapter 1, a sensor pod towed by a tether satellite could be used to investigate layers of the upper atmosphere that are too dense for satellites to orbit through. In 1998 Delta-Utec and Tether Applications presented a more advanced idea, involving a daisy-chain of up to eight research subsatellites connected by tethers to a larger mother satellite. This would enable synchronized, multipoint measurements in the upper atmosphere. They called their idea LADDERS, an acronym for Low-Altitude Daisychain-Deployed Expendable Research Satellites. The total tether length could be something between 40 and 100 km (25 and 60 miles).

Deployment would start with the ejection of one subsatellite from the mother satellite vehicle. Ejection with a speed of about 1.5 meters per second (5 feet per second) would provide enough momentum to deploy over 1 km (0.6 mile) of tether from a miniature version of the flight-proven SEDS deployer (as used on the experimental missions SEDS-1, SEDS-2, and Tether Physics and Survivability [TiPS]) mounted in a second subsatellite still attached to the host vehicle. After deployment of the first kilometer the tension in the tether due to the gravity gradient will be sufficient for continued deployment; the tether will be rolled out automatically. Full deployment of the first tether segment would then trigger the ejection of the second satellite, which in turn would pull out a second tether segment from a deployer in the third satellite, and so forth.

The lower the subsatellites could reach down into the upper atmosphere, the more useful the scientific data but the higher the aerodynamic drag. Due to the amount of heat created by drag, the lower limit for LADDERS was determined to be an altitude of about 125 km (80 miles). Most of the drag would be experienced in the bottom 15 km (9 miles) of the tether chain, which has to be compensated for by a sufficient amount of mass orbiting at higher altitudes to prevent the system from de-orbiting too soon. The lower tether segments would need to be very thin to reduce the air drag as much as possible. They could consist of a single tether strand of about 0.4 mm (0.016 inch) thick. Having single-stranded tethers in the lower parts leads to a 10 percent risk of losing, within 2 days, a lower satellite by a meteoroid cut. On the other hand, the use of a thicker tether or Caduceus at the bottom segments shortens the nominal mission duration by 30 percent or more. A detailed trade-off between the risk of losing a satellite and a longer mission duration would thus be an important issue for the detailed design of a LADDERS mission. The upper tether segments that are less affected by drag could be made of a thicker multistrand Caduceus tether (as used in the Young Engineers' Satellite [YES] project).

Depending on the mass of the mother satellite and subsatellites, a lifetime of about 2 days was foreseen before the whole system would de-orbit. However, this could be increased by cutting the tether segment of the lowest subsatellite once it has reached the bottom-limit altitude of about 125 km (80 miles). Because of the resulting momentum exchange the reduced daisychain system would get an up-boost, enabling it to stay in orbit for up to another day. Another possibility to increase the lifetime of the system is to compensate the drag using rocket thrusters.

Let's Stay Together

Since the invention of the telescope and its application in astronomy, there has been a continuing strive for ever-larger systems. Bigger telescopes collect more light, and are therefore better able to observe faint objects. They can thus see galaxies, stars, and planets that shine very weakly or that are very far away.

Another important benefit of larger telescopes is that they are able to achieve better angular resolutions. The resolution of a telescope is the minimum angular distance at which two objects can still be seen as individual sources of light; objects separated by an angle smaller than the instrument's angular resolution cannot be resolved. For example, through a small telescope the two components of a double star may appear like one single dot of light, but a large telescope enables distinguishing the two individual stars. The resolution of a telescope is a function of its diameter, or, to be precise, is proportional to the wavelength of the collected radiation divided by the diameter of its primary lens or mirror. The larger the diameter, the better the resolution and thus the better the telescope is able to distinguish individual objects. This is true for any type of telescope, whether it is designed to detect visible light, infrared radiation, radio waves, or any other sort of electromagnetic radiation.

Hermann Oberth, the German spaceflight pioneer, proposed as early as 1923 to build giant mirrors using a rotating spacecraft. The spacecraft would deploy several tethers, which would fly outward due to the centrifugal forces caused by the rotation. Astronauts would then interconnect these radial cables with other cables, creating a kind of spider web. To this structure more cables would be attached until a giant, disk-shaped network of cables would be created. In the openings between the cables Oberth intended to place mirror elements, resulting in the creation of a gigantic mirror. He was thinking in terms of a diameter of 150 km (100 miles)—a truly daring idea at a time when the basics of rocketry were still being developed. Oberth's mirror could be used to reflect sunlight to cities or agricultural areas on the night side of Earth. A military use he advertised would be to intensely focus sunlight on one small spot on Earth's surface, creating a sort of "death ray" to blow up ammunition depots or scorch marching armies. A peaceful application of this feature could be the melting of icebergs that form a hazard to shipping. Oberth also proposed to use his mirrors to improve the climate at the poles by heating them with reflected sunlight, but today's concerns about climate change would not make this a good selling point. The principle of the gigantic mirror could also be used to build enormous telescope mirrors for astronomical purposes, but it would even today be quite a feat to build a large disk structure out of tethers, and also to accurately point such a flexible construction.

Instead of increasing the diameter of a single telescope, good resolutions can also be obtained by linking smaller telescopes positioned at a distance from each other. These can be used to simulate a much larger telescope with a diameter equivalent to the distance between the smaller telescopes, called the baseline. The small telescopes cannot collect as much radiation as can a single telescope with a diameter equal to their baseline. Nevertheless, for the objects they are able to see, the combination will have the same angular resolution as the giant telescope they simulate. This technique of combining smaller detectors to attain better resolutions is called "interferometry."

Astronomers have long been using interferometry to combine signals from two or more radio telescopes to obtain measurements with better resolutions than could be obtained with individual antenna dishes alone. Recently, terrestrial optical telescope arrays also have been built for scientific research requiring very high resolution images, such as the measurement of the diameters of stars and the search for extrasolar planets. Creating interferometer arrays for visible light frequencies is more difficult than for radio waves, because it requires more precise knowledge and control of the distance between the individual telescopes (due to the shorter wavelength of optical light in comparison to those of radio waves).

Astronomy is using telescopes in space because they offer superior observation conditions. Far above Earth's atmosphere, observations are free from disturbances caused by temperature differences in the air (which makes stars twinkle), and all radiation can freely reach the instruments without being blocked or absorbed by various gases. Moreover, without having to cope with the rotation of a planet, in space astronomical objects can be tracked for very long durations. Many astronomical gamma-ray, x-ray, ultraviolet, optical, and infrared observatories have been launched into orbit, of which the Hubble Space Telescope is the most famous example.

Scientists now also dream of deploying interferometers in space. NASA's MAXIM (Micro-Arcsecond X-ray Imaging Mission) concept, for example, envisions flying as many as 33 satellites in concert to create a huge x-ray interferometer. MAXIM's resolution should be high enough to image black holes. The European Space Agency is meanwhile working on its Darwin mission, which calls for at least three space telescopes and a fourth spacecraft serving as a communications hub. Operating together, they should be able image to Earth-like planets orbiting other stars. NASA's Terrestrial Planet Finder (TPG) mission concept has more or less the same objectives. Another NASA mission, Submillimeter Probe of the Evolution of Cosmic Structure (SPECS), requires far-infrared/submillimeter telescope satellites to be spaced 1 km (0.6 mile) apart to study the first (and therefore farthest away) galaxies that formed in the early Universe. It should provide an angular resolution comparable to that of the Hubble Space Telescope, which is difficult to reach with a single infrared telescope due to the large wavelength of infrared light in comparison to visible light. Because angular resolution is proportional to the wavelength divided by the telescope diameter, we need a larger telescope to achieve the same angular resolution in infrared as with visible light.

However, astronomical interferometry in space is tricky; while Earth offers a firm, solid foundation for the arrays, there is no solid ground in free space. Individual space telescopes could be connected by long and rigid structures, but that quickly leads to unwieldy, extremely massive constructions that are too difficult and expensive to launch, assemble, and maintain in space. On the other hand, interferometers consisting of several free-flying space telescopes require extremely accurate, three-dimensional distance measurement techniques and super-precise active attitude and position control for all spacecraft simultaneously. That is also difficult and expensive to implement, and attitude control thrusters require propellants of which only limited supplies can be taken onboard. Active control using propulsion systems can also disturb the ultra-sensitive instruments and measurements required for many interferometry applications. In addition, thruster exhaust could contaminate sensitive optical equipment and thermally obscure a space telescope's vision.

A solution that tether technology offers is the use of nonrigid physical connections. Flexible cables can connect the individual spacecraft in an array, and as long as there is tension on the cables the distances between them can be kept constant to a high degree of accuracy (although the stability of the arrangement may be an issue). A simple array could consist of only two tether-connected space telescopes, but there are basically no limits to the number of spacecraft that can be involved. Three-dimensional tether constellations are also possible, for example a pyramid or cube formation. Space telescopes can be packed close together during launch, and then spread out into space while deploying tethers between themselves. This principle has already been applied to some simple and experimental constellations developed by the Aerospace Corporation, involving their Picosats and MEPSI (Micro-Electro-mechanical Systems-based PicoSat

Inspector) satellites. Using tethers instead of propulsive systems simplifies stationkeeping and does not cost any propellant. Moreover, conductive tethers could be used to transfer data and electrical power from one satellite to another.

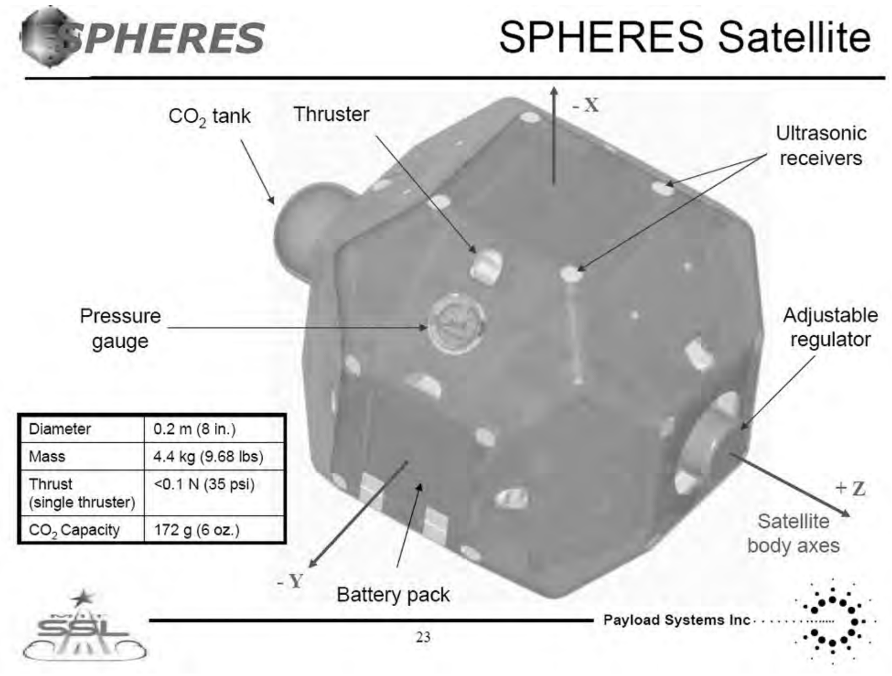
Making the constellation spin results in centrifugal forces that keep the spacecraft at the required distance from one another, while maintaining the necessary tension in the tethers. However, many astronomical interferometry applications require that the telescope arrays not spin but rather remain motionless throughout an observation period. Physicist Young Bae has proposed a novel system that relies on lasers and tethers to achieve nanometer distance accuracies in spacecraft constellations spread out over several kilometers. Light being reflected by a mirror results in a minute but measurable amount of thrust (the principle behind the concept of solar sailing), so laser light can be used to generate minute pushing forces. Bae's idea involves laser beams that are reflected back and forth between pairs of spacecraft within a formation. The resulting outward push is balanced by the inward pull of the tension in the tethers linking the satellites. The same laser beams can also be used to very accurately measure the distance between the satellites according to the method of laser ranging; if we measure how long it takes the light to reach another spacecraft and reflect back, and we know the speed of light, then we can determine how far away the other spacecraft is.

Any tether has some inherent tension or "springiness," which will try to pull spacecraft together if not compensated for by centrifugal force or laser light propulsion. Varying the intensity of the laser beams, and thus the light thrust, makes it possible to actively maintain the desired distance by balancing the tether tension and the outward push of the lasers. This should enable even more precise formation flying than with tethers alone.

NASA is interested in the idea, and its (recently closed) Institute for Advanced Concepts funded the first stage of Bae's laser-tether project. However, there are also other possibilities, such as the use of electromagnets to make individual spacecraft attract or repel each other to control their relative position within a formation.

Nevertheless, we have already seen that the deployment of tethers in space can be very tricky. In addition, vibrations in the cables and pendulum motions of the connected spacecraft could cause disturbances in the measurements, potentially making it impossible to reach the extreme accuracies needed for many planned interferometry missions. No space agency will be willing to develop and launch a full-fledged, billion-dollar, tether-based space interferometer system without a thorough proof of the tether formation flying concept.

The Massachusetts Institute of Technology (MIT) is already conducting



SPHERES Satellite

Diameter	0.2 m (8 in.)
Mass	4.4 kg (9.68 lbs)
Thrust (single thruster)	<0.1 N (35 psi)
CO_2 Capacity	172 g (6 oz.)

Figure 5.2: Diagram of a single SPHERES satellite. (Courtesy of NASA/MIT.)

experiments on formation flight control for future tethered interferometers, and specifically for NASA's SPECS mission. They developed and use a laboratory testbed called SPHERES, an acronym for Synchronized Position Hold Engage and Reorient Experimental Satellites. SPHERES consists of a number of autonomous, bowling-ballsized satellite units interconnected by thin wires, a laptop computer acting as the ground station, and some small beacons that the satellites use to determine their position and attitude. The indoor satellites are equipped with cold-gas thruster maneuvering systems that use carbon dioxide as propellant, and strongly resemble the hovering Training Remote used by Luke Skywalker to train his light saber skills in the first *Star Wars* film. (Fig. 5.2).

The system has first been used to simulate two-dimensional tether spacecraft formations on the ground by mounting the SPHERES satellites on air cushions (like on a hovercraft) and putting them on an extremely flat and smooth floor. Levitating on high-pressure air, the units can freely slide across the floor, simulating microgravity conditions in two dimensions. This setup has been used to improve theoretical mathematical modeling of tether satellite formation behavior. SPHERES has also been flown onboard a special NASA airplane that can create microgravity conditions for about 20 seconds at a time by flying parabolic trajectories.

This allows tests of three-dimensional formation configurations, albeit for very short durations.

Tests inside the ISS, which provides long-duration microgravity conditions, are currently ongoing. The first, single, SPHERES testbed unit for system checks was launched to the station onboard a Progress freighter spacecraft on April 24, 2006. Astronauts commanded it to do a variety of maneuvers and tested the robot's ability to solve problems by blocking one of its thrusters in the "on" position. The robot correctly figured out the problem, turned the thruster off, and returned to stationkeeping. The second satellite was delivered to the ISS on Space Shuttle mission STS-121, allowing tests of a two-satellite configuration. A third satellite followed on STS-116, so that tests with three satellite formations could be started.

However, tests of formation flying with large distances between individual spacecraft can be done only in free space, outside the space station. Stanford University and Santa Clara University have proposed Emerald, a low-cost mission for the validation of formation-flying technologies, including tethers. It was planned to be launched with the Space Shuttle in 2003. However, apparently no progress has been made on this project; the project's website is currently unavailable, which is usually not a good sign. At the moment neither this mission nor any other similar concept is seriously being financed to fly in the near future. In the meantime, the technology needed to fly interferometer arrays in space without the use of tethers is advancing rapidly, so whether tethers will be competitive in this domain remains to be seen.

Gravity in Space

In Chapter 1 we saw that it is often handy to have artificial gravity in the otherwise microgravity conditions in orbit (see the section Satellite Experiments). It makes life for astronauts much easier and healthier. We have also seen that to prevent motion sickness, two rotations per minute are about the maximum allowable. That means that the simulation of Earth gravity (1 gravity, or 1*g*) requires a rotational radius of 220 meters (720 feet), and the lower Mars gravity of 0.38*g* requires a radius of 90 meters (300 feet).

The creation of artificial gravity using two tethered spacecraft was the first ever tether experiment performed in space, on Gemini 11 (see Chapter 4). The gravity level reached during that mission was very low, but it proved that the concept works.

An artificial gravity spacecraft could consist of two modules and a tether deployment system that are launched together. When the modules undock and move away from each other, they would unreel a long tether. The amount of rocket thrust and thrust duration needed to spin up the assembly is smallest when the radius is at its maximum. However, it will probably prove best to first deploy a limited length of tether and then initiate some rotation, to provide a steady pulling force to deploy the rest of the cable. That would prevent the bouncing effects and tether loops experienced by Gemini 11.

A rotating tether system to generate artificial gravity is an important part of the famous Mars Direct concept first published by David Baker, Owen Gwynn, and Robert Zubrin in 1990, and subsequently in Zubrin's popular book, *The Case for Mars*. It describes how a crewed, relatively low-cost mission to Mars could be based on known technology and much already-existing equipment. The Mars Direct designers propose that on the way to Mars, the manned spacecraft is kept connected to its launcher's upper stage by a 1.5-km-long (0.9-mile-long) tether. A once-per-minute rotation of the assembly around the common center of mass (which lies closer to the crewed module because it has a higher mass than the upper stage) would let the astronauts experience the same level of gravity as on the Martian surface. This is expected to prevent many of the physiological problems that are typical for long duration flights in microgravity. It would ensure that the crew would be able to work effectively right after landing, being already used to Martian gravity conditions. Otherwise, spending the whole half-year flight to the red planet in microgravity, the astronauts might not even be able to walk; even astronauts flying half-year space missions onboard the ISS usually need to be supported after landing back on Earth. Near Mars the upper stage and tether would be discarded, leaving the crewed spacecraft free to maneuver and land unhindered. A similar low-mass artificial gravity system was already proposed as part of a Mars expedition concept that TRW studied for NASA in 1963. Their design used a 152-meter-long (500-foot-long) tether and a rotation rate of two rounds per minute to generate Mars-like gravity conditions inside the piloted spacecraft.

Tether artificial gravity systems could be tested in Earth orbit before being used on interplanetary missions. In August 2008 the Mars Society, of which Zubrin is president, announced that it intends to develop and fly a small tether satellite, the Tethered Experiment for Mars inter-Planetary Operations (TEMPO 3 or TEMPO cubed). The project was selected as part of a competition. Tom Hill, a founding member of the Mars Society, submitted the winning proposal. The satellite is to be based on standard CubeSat nanosatellite platform equipment, which is often used by amateur groups and universities seeking to develop inexpensive, small satellites. In a news announcement, Zubrin said that his group aims to supplement research on the feasibility of long-term space flight for humans, and as part of that seeks to develop technology to provide gravity in space. He further commented, "Similar problems existed in the past, when aircrews flew at high altitude and low oxygen levels. The technological solution of providing oxygen was frowned upon by aviation doctors in favor of trying to 'negate the effect' of the low oxygen through medication. Today, flight crews use oxygen at high altitudes, and we expect astronauts to travel with gravity."

The Dutch company Delta-Utec, of the YES and YES-2 tether satellites, has proposed a much more ambitious system named Mars-g. This involves what is basically a small space station consisting of a crewed "hab," a tether system, and a passive module acting as a countermass. Astronauts would dock their Soyuz spacecraft to the hab, then disconnect the countermass module, unreel the tether, and initiate a rotation using a rocket motor on the hab module. Navigation sensors will need to be able to cope with the rotation, but that is in principle not a problem as many existing satellites and interplanetary probes (so-called spin stabilized spacecraft) constantly rotate as well. Antennas and solar arrays that need to be pointed at fixed locations can be put on mechanisms that rotate against the movement of the habitat—what are called de-spun platforms. Maneuvers using rocket thrusters can also be performed while the assembly is rotating, as long as the thrust is low enough that the centripetal force can keep the tether taut. Series of short bursts of rocket thrust at the right moment during each rotation can result in the same change in velocity and direction as a single long thruster burn.

The level of gravity could be controlled simply by varying the rotational radius, without the need for rocket propulsion. Just like when a spinning ice skater draws in her arms, so will the assembly start to rotate faster when the tether is reeled in. Conversely, when the tether is further deployed the rate of rotation will diminish (this is called the principle of angular momentum conservation, which states that for a simple rotating system of two masses connected by a tether, the rate of rotation multiplied by the radius squared remains constant; Fig. 5.3).

As a result, experiments can be done at various constant levels of artificial gravity, making it possible to check what happens to a crew living under lunar and Martian gravity conditions for extended periods of time. The varying gravity conditions would also be very useful for a range of other unique experiments, as we currently can only do tests in microgravity (in orbit) and conditions of 1*g* or higher (on Earth, and using a centrifuge). The rotation could be stopped by use of the rocket motor, and the tether may be completely reeled in to facilitate crew exchanges. Subsequently the tether could be redeployed and the assembly be spun up again. The Mars-g space station could be used for various experiments during years of operation,

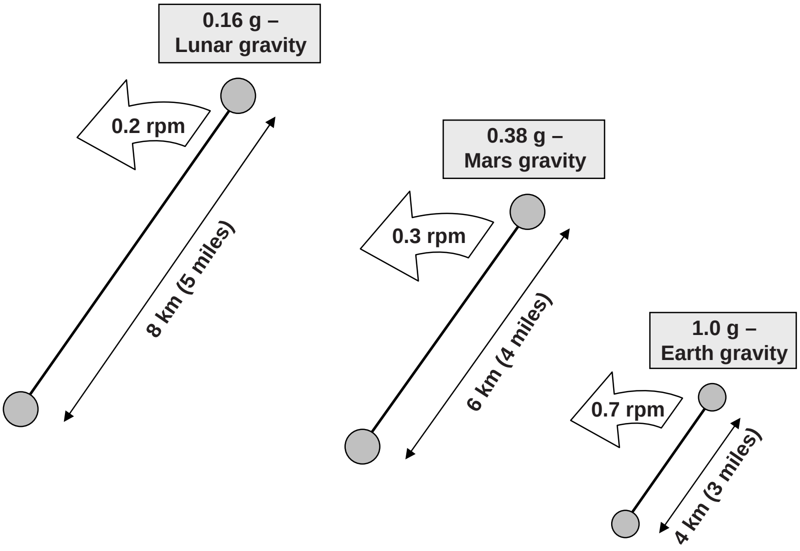


Figure 5.3: Gravity levels can be changed by varying the length of the tether only, according to the principle of angular momentum conservation.

always providing the possibility to stop a mission and a return to Earth at any moment (something not possible during an actual mission to Mars).

Walking inside the living module of a rotating assembly, going around two times per minute and creating a 1*g* environment, would be just like on Earth. However, running would result in some peculiar, very un-Earthlike phenomena. A sprint in the same direction as the module is moving effectively increases the runner's rotational velocity, resulting in a higher level of artificial gravity. Thus, the faster one runs, the heavier one feels. A sprint against the direction of the rotation has the opposite effect: it decreases the runner's rotation speed and thus the gravity level the runner experiences. In that direction, running will enable the runner to lose weight fast, but only as long as he or she keeps moving. Inside a rotating module with Earth-like gravity, one could feel about 20 percent heavier or lighter by running, depending on the direction in which one moves. Using a motorbike to get to 160 km/h (100 miles per hour), one could go fast enough to fully compensate the station's rotation, effectively not rotating at all and thus become weightless—except that speeding on a motorbike would not be feasible inside what is probably a quite small living module.

However, rotation is not really necessary to achieve a low level of gravity inside a spacecraft. We have already seen that two satellites connected by a tether and orbiting a planet will automatically assume a vertical position due to the gravity-gradient stabilization principle. The upper satellite is effectively orbiting too fast and tries to pull away, while simultaneously the lower spacecraft tries to fall down. If an astronaut were to inhabit the top spacecraft (module) in such a gravity-gradient stabilized system, he would also fly around Earth too fast and therefore be flung against the ceiling (which he could regard as being the floor of his accommodation). This would thus enable him to stand up as if there were gravity, but upside down with respect to Earth's surface. At the same time, his colleague in the lower spacecraft would effectively be pulled back to Earth and therefore be able to stand on his module's floor, upright with respect to Earth. In effect, inside each habitation module there exists an imbalance between the centrifugal force caused by the system's rotation around Earth and Earth's gravitational force, causing a net force that the astronauts perceive as gravity. The centrifugal and the gravitational force are exactly equal but opposite at the system's center of mass, where the resulting gravity level is thus zero (Fig. 5.4).

A gravity-gradient stabilized space station consisting of two modules connected by a 50-km-long (30-mile-long) tether and circling in a low Earth orbit could provide its inhabitants with about 1 percent of the gravity level we experience at Earth's surface (inside both the upper as well as the lower module). It would not be enough to make real walking possible, because the astronauts would bounce up with every step, but the low gravity level would

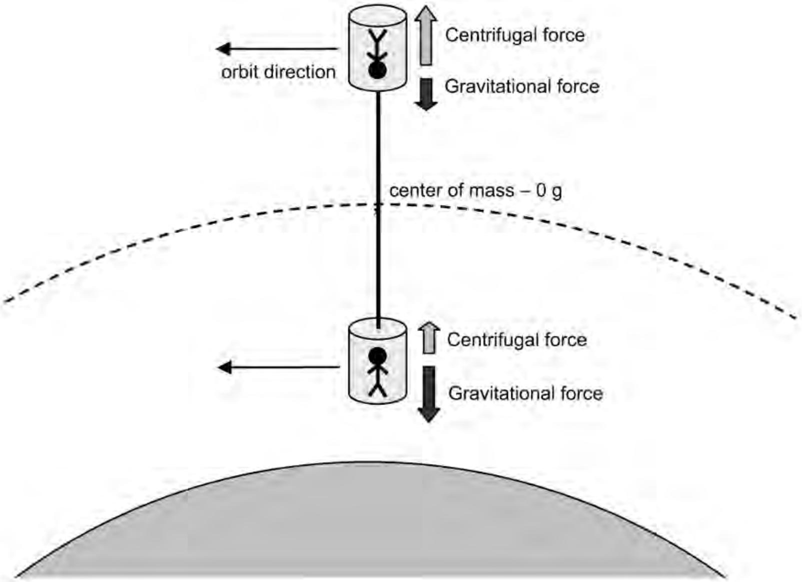


Figure 5.4: Astronauts living in a gravity-gradient stabilized space station would experience a low level of gravity inside each habitation module.

make life in space a bit easier. Drinks could be poured into glasses, tools would gently fall down instead of floating away to unreachable places, and astronauts could enjoy a real shower. There is also a good chance that the many physical and psychological problems connected to life in microgravity would be considerably alleviated. Moreover, with such a station it would be possible to do experiments in gravity levels ranging from 0*g* (in the system's center of mass, exactly between the two modules) to 0.01*g* (inside each module). A small elevator cabin riding the tether between the two modules would make it possible to precisely choose the required gravity level in this range.

One Up, One Down

In Chapter 1 we saw how a momentum exchange tether works. When an orbiting spacecraft vertically deploys a long cable with a mass at the end, and that cable is subsequently cut, the spacecraft moves into a new orbit. This orbit has either a higher or a lower average altitude than before (it will be an elliptical orbit), depending on the direction in which the mass is initially pushed away. The deployed mass also enters a new orbit; if the mother spacecraft goes up into a higher orbit, the mass or subsatellite will go down into a lower orbit, and vice versa.

Momentum exchange tethers can thus be used to alter the orbits of satellites without propulsion, just by using the momentum of the cable. We have seen that the concept has already been validated by the experimental Small Expendable Deployer System (SEDS-1) and YES-2 missions, where the momentum exchange principle was used, respectively, to de-orbit a spacecraft and to return a small reentry capsule (as described in section Satellite Experiments in Chapter 4).

An operational application could be the use of YES-2 type equipment on the ISS. Some research performed onboard this large orbital laboratory requires samples of biology and material science experiments to be returned to Earth for further analysis. Currently such samples can only be flown back by the large Space Shuttle, or alternatively by the Russian Soyuz, which is rather small and consequently has little storage space. Both vehicles visit the station for crew exchanges and resupply only a couple of times a year, so the opportunities to return anything to Earth are relatively rare. When the Space Shuttle is phased out in 2010 (as currently planned), for a couple of years only the Soyuz will be available for cargo return (the uncrewed transportation vehicles Progress and ATV cannot return to Earth intact, but instead are destined to burn up in the atmosphere after delivering supplies to the ISS). NASA's new Orion crew capsule will also have only very limited cargo space. Especially with biology experiments, samples often deteriorate quickly and thus need to be flown back as soon as possible after completion of the onboard experiment.

The small company Delta-Utec has proposed a Space Mail system, similar to their YES-2 demonstrator, which could be used to de-orbit sample return capsules using a swinging tether. The Space Shuttle or other large launch system could deliver a number of such capsules together with a single tether deployment system to the ISS. When needed, a capsule could be hooked up to a tether and returned to Earth. As a capsule would be swung to a sufficiently lower altitude for de-orbiting, in reaction the ISS would simultaneously enter a slightly higher orbit (momentum exchange). The Space Mail system would thus also provide a free reboost to the station, partly compensating for the orbit deterioration caused by the tiny but continuous atmospheric drag force present at the nominal orbital altitude of the ISS. Reboosts are currently performed using the station's own rocket orbital maneuvering system as well as the more powerful thrusters of visiting Progress and ATV cargo spacecraft, but they cost a lot of propellant.

Unfortunately, the stringent safety rules imposed after the tragedy with Space Shuttle Columbia and the very tight budget available for future ISS operations and developments do not offer much hope for the implementation of a Space Mail system on the station. The risk of a return capsule accidentally colliding with the ISS or a tether wrapping itself around the station will probably be too high; in addition, no money is set aside for the development of the system, and there is no launch slot available in the current ISS flights planning.

An idea for a much more advanced momentum exchange tether system is what tether enthusiasts call a "bolo"—a free-flying, rotating tether system that could be used to transfer spacecraft to higher orbits. The name is probably derived from the bolo or more correctly bola, a throwing rope with weights at both ends that is used to hunt animals by ensnaring their legs.

Imagine an extremely long cable, 100 km (60 miles) or more in length, in an elliptical orbit and spinning vertically like a sling. On one end it has a large ballast mass and on the other a spacecraft catching and docking device. Because the ballast has a much higher mass than the rest of the cable, the center of mass and thus the center of rotation lies close to the ballast mass. If the tether's rotation is timed just so that when the bolo reaches its perigee the tether is vertically straight below the bolo's main body and swinging backward, it is possible to match the velocity of a target satellite that is moving slower (Fig. 5.5).

When at the bottom of the tether's rotation the catching device is

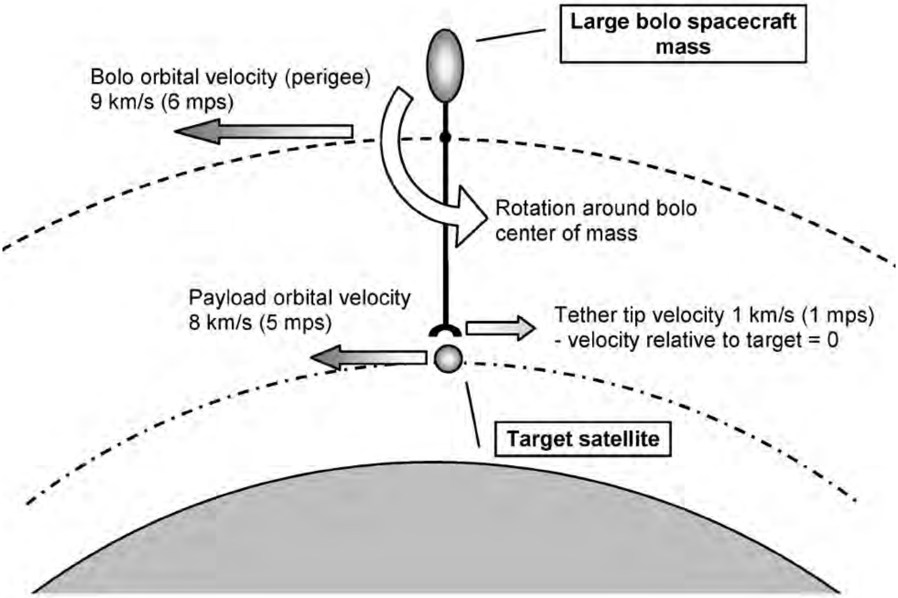


Figure 5.5: A backward-rotating bolo tether tip could match its velocity to that of a spacecraft on a suborbital trajectory and then catch it.

swinging by at low altitude, the payload spacecraft hooks itself to the tip's docking clamp (or is actively caught by the bolo). Half a tether rotation later, when the tip with the docked spacecraft reaches its maximum altitude, the satellite is released at a higher velocity (the bolo's orbital speed plus the tip's rotational speed) and thereby tossed into a higher orbit (Fig. 5.6).

For this to work, the bolo needs to follow an elliptical orbit and catch the target spacecraft when it is moving through its perigee; only then can its orbital velocity be higher than that of a satellite in a lower orbit. As we have seen in the section Orbits in Chapter 1, a satellite in a high circular orbit moves slower than one in a lower circular orbit.

A series of bolo tethers, each tether passing a spacecraft onto the next, could be used to achieve even larger orbit changes than a single system. For example, one tether system could catch a spacecraft from a very low orbit and swing it into a somewhat higher orbit. Another bolo picks it up from there and puts the satellite into a geosynchronous transfer orbit (GTO). A third tether catches the load again and imparts sufficient velocity to it so that it reaches escape velocity. A satellite initially orbiting just above the atmosphere could thus be slung all the way into an interplanetary orbit around the Sun, and all this without using any rocket propulsion and propellant. The process can also be reversed: a bolo tether catching a satellite

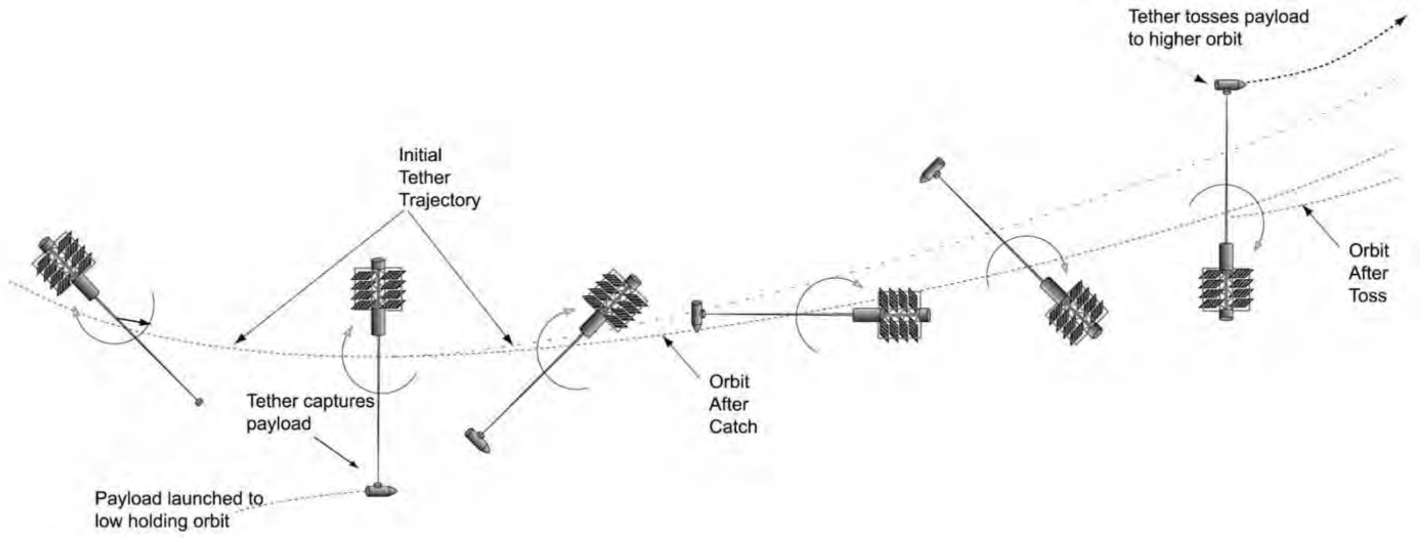


Figure 5.6: The principle of a bolo momentum exchange tether used to carry satellites into higher orbits. (Courtesy of Tethers Unlimited, Inc.)

in a high orbit at the peak of the cable's rotation, and subsequently releasing it into a lower orbit. This concept would be useful for catching interplanetary spacecraft coming back to Earth (for example, the reentry capsule of a Mars sample return mission), and putting them into orbits around Earth. With a series of tethers, such a spacecraft could then be brought down into a low Earth orbit and made to fall into the atmosphere in order to land on Earth without using any onboard propulsion system (which would otherwise have to be flown all the way to Mars and back, resulting in a heavy mass penalty).

When a "catching" bolo is put in orbit around the Moon or another planet like Mars, it could be used to grab an incoming spacecraft launched by another, "throwing" bolo system in orbit around Earth. In this way, an interplanetary transportation system could be created, as was shown by Robert L. Forward in a scientific paper he published in 1991. The concept has been further developed by him and Robert Hoyt for their company, Tethers Unlimited, as the Mars–Earth Rapid Interplanetary Tether Transport (MERITT) System.

Since the Moon has no atmosphere, a bolo in lunar orbit could even go one step further than putting payloads in lower orbits: it could place spacecraft directly onto the lunar surface! In 1978 tether pioneer Hans Moravec proposed a lunar "skyhook," also known as a "rotovator," consisting of a massive central facility and two very long tether arms in rotation (the idea was based on the original Earth-orbiting skyhook concept of Dr. John McCarthy, who invented it as an alternative to the space elevator in the early 1950s). These tethers would have the same length as the orbital altitude of the central facility, and during the system's rotation their tips would thus periodically reach the surface of the Moon. The rotovator would rotate in the same direction as its orbit, and at such a rate that the velocity of each tether's tip would be equal to the orbital velocity of the system's center of mass, that is, the center facility. When swinging down backward and reaching the lunar surface, a tether tip's velocity relative to the Moon would thus be zero; as a result it would be able to gently place an object on the ground or pick it up. The tether arms could be thought of as spokes on a giant wheel rolling over the Moon (Fig. 5.7).

The large mass in the center of the rotovator ensures a steady orbit even when catching and releasing payloads, as long as they have much lower masses. The tether arms would need to be very long, because if the central facility would fly too low, its orbit would be significantly disturbed by the Moon's inhomogeneous gravity field. Moravec's system employs two tethers, but a bolo using a single tether arm with a grapple mechanism on one end and a countermass on the other could be used as well. Such a system would

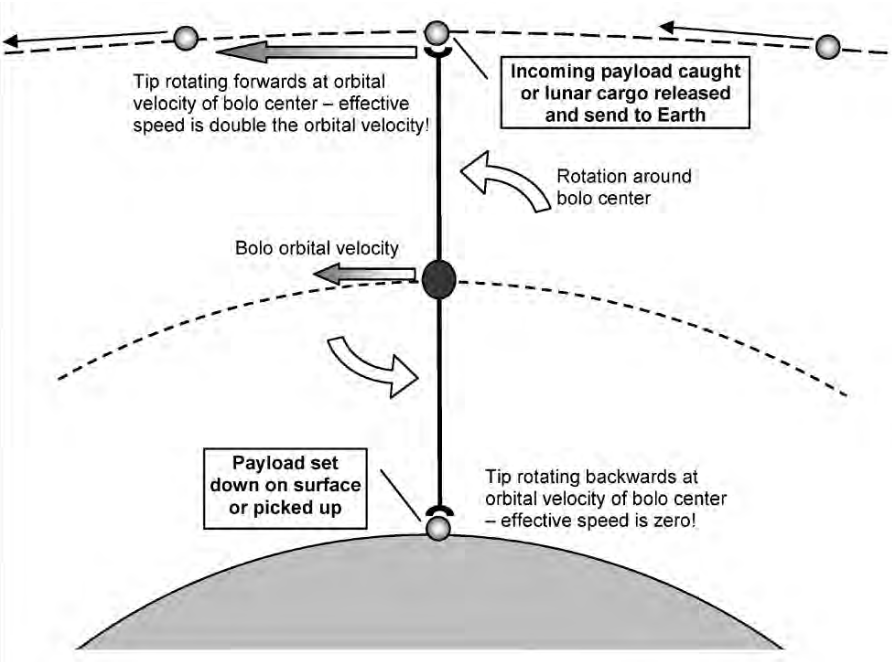


Figure 5.7: A lunar rotovator could gently place payloads onto the surface of the Moon, or pick them up and launch them to Earth.

rotate around the common center of mass, but as long as the distance from the grappling end of the tether to the rotational center is the same as from there to the surface, the system should work okay. Rotating and orbiting the Moon, a lunar rotovator, or "lunavator," with one or two arms could capture payloads flying in from Earth and set them down onto the surface of the Moon. At the same time it could pick up cargo from the Moon and half a rotation later send it to Earth, by releasing the cargo at a tether tip velocity that is twice the center facility's orbital velocity.

Although the rotovator never stops spinning, due to the gigantic scale and because its tip will have zero horizontal velocity with respect to the surface, people on the ground will not perceive it as a rotating tether. To them it will look like a long cable reaching straight down vertically from the sky, then retreating back up exactly the same way. Depending on the tether length and the rotation speed (the combination always needs to be selected so that the tip speed at the lunar surface is zero), lunavators can be made to periodically touchdown at the same single spot, at several fixed spots or at any number of varying locations every orbit. For transportation to and from a moon base, we may want one that drops by once every orbit. However, a rotovator that makes multiple rotations per orbit could service more than one lunar station. We may also use the tether as a kind of helicopter that picks up a payload at one site and then, after one or multiple rotations, drops it at another surface location without releasing it into space.

Normally the time available for the rotovator to deposit and pick up payloads on the lunar surface would be very short, on the order of seconds. However, by deploying additional cable from a reel at the tether tip and with the help of rocket thrusters, cargo could be landed ahead of when the tip would normally arrive on the Moon. Likewise, after the normal and very short touchdown time has passed, the grapple system at the end of the tether could be kept on the surface for a bit more time by unreeling cable as the main tether starts to pull away. This technique could lengthen the time available for docking and undocking cargo to several minutes, making the concept much more practical.

A rotovator, the name now commonly used for any low-orbiting bolo, could in principle be used on any planet or moon. However, when there is an atmosphere the tether arm will have to move through it at very high velocities, creating a lot of aerodynamic drag and heat that could easily burn the tether through. A rotovator orbiting Earth reaching all the way to the planet's surface is therefore very probably unfeasible.

Of course there is a catch in the use of momentum exchange tether launch systems: the momentum and kinetic energy that a released spacecraft gains have to come from somewhere. The source is obviously the bolo or rotovator; a spacecraft thrown into a higher orbit steals momentum from the rotating tether system, which itself therefore ends up in a lower orbit. There is no energy creation in this system, only a transfer of kinetic energy from the bolo tether to the satellite. The higher its own mass in comparison to the payload mass, the less a bolo's orbit will be affected by picking up or launching cargo. To prevent it from entering Earth's atmosphere or crashing onto the Moon, a bolo or rotovator thus needs to have a high mass relative to the mass of the individual payloads it handles. Moreover, the increase in velocity and orbit altitude that it is able to give to its released cargo is very limited if the tether system's mass is not considerably higher than that of its payload.

Launching a sufficiently heavy bolo system would be difficult and costly, and so would in-orbit assembly of separately launched modules. However, a massive bolo system could be built up by starting with a relatively light tether and ballast mass. This system could then start to catch small payloads that are not released, but instead transported up the tether by mechanical climbers (similar to those proposed to go up and down space elevators). In this way the bolo could build up ballast mass near its center of rotation, increasing the mass of the individual payloads it is able to handle. A lunavator could pick up containers full of rocks or water directly from the Moon and haul them up to its ballast mass station.

Nevertheless, after launching one or more satellites (depending on the spacecraft masses, tether mass and length, initial orbit, etc.) a bolo tether will eventually get too close to the surface or atmosphere of the planet or moon it orbits. This could be prevented by using a rocket propulsion system to push it back into its original orbit, but that would nullify most of the benefits of using a bolo system.

However, as with the Debris Shepherd, the bolo could be turned into an electrodynamic propulsion tether by lining it with metal wire and running an electric current through it. This current could be generated by equipping the bolo ballast mass with solar arrays. The Lorentz force caused by the interaction of the electric tether's magnetic field with Earth's own magnetic field would then provide a small but steady push, sufficient to propel the bolo tether system back into a higher orbit.

The same Lorentz force could also be used to initiate or increase the bolo's rotational speed, because as long as the center of mass of the bolo is not exactly in the middle of the tether, the electrodynamic force will cause an acceleration of the rotation rate. However, it would not be needed to adjust the rotational velocity during operation, because catching and throwing payloads does not affect the rotation rate of the bolo. If this is somewhat hard to imagine, remember that at the moment of rendezvous the velocity of the target spacecraft and the tether tip are the same; they simply connect without changing their velocity.

This concept of combining a momentum exchange tether with an electrodynamic propulsion tether for transporting orbital payloads was invented in the late 1980s by Dr. Robert Hoyt of TUI. He called it a Momentum-eXchange/Electrodynamic-Reboost (MXER) tether system. The great benefit of this system is that it can swing satellites into higher orbits and then replenish the transferred orbital energy—all without using any propellant. The MXER can give a spacecraft the equivalent of a high-thrust impulsive rocket burn, putting it into a much higher orbit in a very short time with a powerful burst of momentum exchange. Then it can slowly reboost its own orbit over several weeks or longer. The energy required for the MXER ultimately comes from the Sun and is thus available in space for free; sunlight is converted into electricity by the MXER's solar arrays, subsequently turned into orbital energy by the electrodynamic tether, and then transferred via momentum exchange to a target satellite that uses it to reach a higher orbit.

The practical use of electrodynamic tether propulsion around our planet is restricted to orbits lower than an altitude of about 1000 km (600 miles), because only in that region is Earth's magnetic field strong enough and the ionosphere dense enough to generate a sufficiently powerful Lorentz force. The elliptical orbit of a MXER tether must therefore have a perigee fairly close to Earth. As we have already seen in the description of how orbits work, propulsive boosts near an orbit's perigee will increase the apogee altitude but not the height of the perigee itself. As long as a MXER has a perigee below an altitude of 1000 km (600 miles), it will thus always be able to reboost itself.

However, if the orbit is very elliptical and the apogee very high, the bolo spends little time near its perigee and is thus only able to use electrodynamic propulsion for a short time each orbit. That means that MXERs intended for use at high altitudes, such as those at the end of a series of bolos that are used to sling payloads into interplanetary orbits, may require long reboost times.

Another drawback is that electrodynamic propulsion cannot be used for tethers in orbit around the Moon or Mars, because these have extremely weak magnetic fields. Bolo tethers in orbit there would have to raise their orbits by other means. Using chemical rocket propulsion does not make much sense, because most of the benefit of not having to use any propellant to change the orbits of the target spacecraft would then be lost. Instead solar electric propulsion may be used, which uses sunlight turned into electrical power by onboard solar arrays to run ion thrusters. It does require propellant, but much less than conventional chemical propulsion systems (see Rocket Propulsion Limits and Limitations in Chapter 2).

However, if a bolo tether's own orbit is lowered when it throws out a spacecraft, its orbit is raised when it catches an incoming payload and releases it into a lower orbit. A bolo or rotovator circling the Moon could thus maintain its orbit by throwing and catching equal amounts of payload; sending cargo to Earth lowers its orbit, but catching and releasing incoming spacecraft from Earth subsequently increases it again. In this concept, there is no need for propulsion on the tether. Adjustments in the bolo's orbit could even be made by varying the masses thrown and caught according to the intended increase or decrease in orbital altitude.

The most difficult part of the bolo concept is the rendezvous between the tether tip and the target spacecraft. Not only must the tether swing down into the target's orbit exactly at the moment that the spacecraft is at the right position, but the tip and the target must also move exactly at the same speed in exactly the same direction. Only then will the catching device on the tether be able to grab the spacecraft. Since the orbit of the bolo and that of the spacecraft are different and the tether itself is also rotating, the amount of time for docking the target to the tether's tip is very, very short. In contrast, the Space Shuttle docking to the ISS is an extremely slow process. The shuttle carefully maneuvers to match the orbit of the station in terms of direction, speed, and acceleration. Docking requires a precision of millimeters in position and millimeters per second in velocity. A bolo tip docking to an orbital spacecraft will only be able to match position and velocity for a very short time, as the acceleration rates will never match due to the different orbits and tether rotation. If the docking device does not connect to the spacecraft in an instant, they will inevitably move away from each other. As described earlier for the lunar rotovator, the use of mechanisms to reel in or out the last part of the tether and rocket thrusters on the grappling mechanism may be able to somewhat prolong the time available for docking. However, since in orbit there is no fixed ground, like on the Moon, and as the target spacecraft is moving, rendezvous times will remain very short—probably on the order of tens of seconds. Capturing a satellite with the tip of a rotating bolo tether will be about as difficult as sitting in a rollercoaster and trying to catch an egg thrown up at you from a moving car.

Passing on payloads from one tether to another in a series of Earth-orbiting bolo systems will be even more tricky, as the orbits of all the individual tethers need to be closely aligned; they must lie in exactly the same plane, and the tip of each tether must swing by exactly at the right time and position at the bolo's perigee to be able to catch the target satellite. The problem is that Earth is not a perfect sphere. The resulting small variations in gravity at the same altitude make orbits change continuously. If two tethers in a bolo series start out orbiting in the same plane but at different altitudes, their orbits will immediately start to move so that they no longer share the same orbital plane. Moreover, if their perigees were initially right above each other, the nonhomogeneous gravity field will move them so that very soon they will not be close to each other anymore (Fig. 5.8).

The changes in orbit plane can be prevented by putting all tethers in equatorial orbits (orbits above the Earth's equator), but the movements of the perigee positions cannot. This will make the passing on of payloads from one bolo to another extremely difficult and does not leave much room for mistakes; if an orbiting target satellite is missed by a tether tip, its continuously changing orbit and that of the bolo may not allow another catch opportunity. To stay in the spirit of the previous analogy, this is about as difficult as trying to pass an egg from one rollercoaster to another, with each rollercoaster bolted to a rotating platform.

For interplanetary travel between bolo systems these difficulties exist as well but take a somewhat different shape. Now the peculiarities of the gravity fields of two planets have to be taken into account, and moreover each planet is moving in its own orbit around the Sun. On the other hand, the long time it takes a spacecraft to fly from one planet to another allows for some adjustments of its interplanetary orbit with limited use of onboard

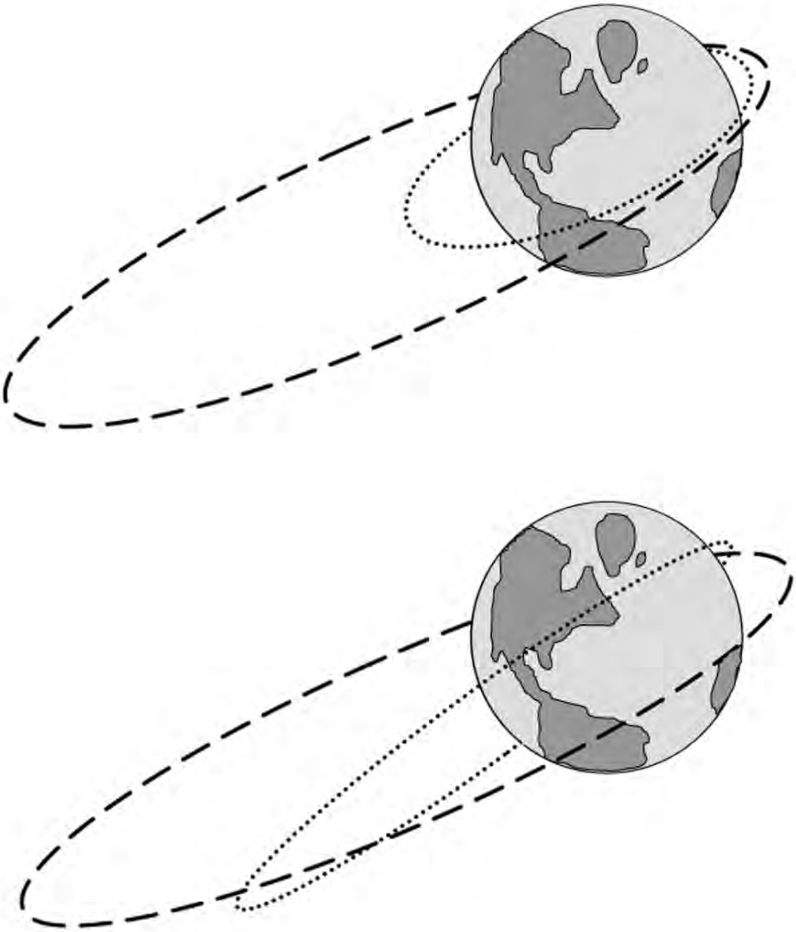


Figure 5.8: Two initially compatible bolo orbits will soon evolve so that they no longer lie in the same plane.

propellant. If trajectory measurements show that a spacecraft will arrive at the wrong moment or place to be caught by a bolo, its orbit may be adjusted slightly to offer a better rendezvous opportunity.

The development of a tether tip grappling system able to quickly connect to a target spacecraft is also a major challenge. In the spring of 2005, engineers from NASA's Marshall Space Flight Center and faculty and students from Tennessee Technological University tested one solution for this problem. They came up with a concept involving a boom on the target spacecraft and a box-like structure on the end of the tether. When the boom goes through an opening in the box, a mechanism inside latches onto hooks on the end of the boom. When the satellite needs to be released, the spacecraft reverses the hooks on the boom and falls away. Testing of this system involved a simulated satellite of about 12 kg (25 pounds), equipped with a stabilization gyroscope, batteries, sensors, and a camera. To simulate the free-fall conditions in space, the payload was shot up from the floor to the box and then grabbed in midair by the catch mechanism hanging from the laboratory ceiling, about 10 meters (30 feet) off the ground. With nearly 50 successful catch demonstrations, the testing successfully demonstrated the viability of the technique.

Tethers Unlimited has proposed a small experimental tether system to address some of the challenges facing the development of a MXER. This Microsatellite Tethered Orbit Raising QUalification Experiment (µTORQUE) system is designed to fly as a secondary payload on the upper stage of a large rocket. After the launcher has released its primary payload into GTO, the µTORQUE system bolted to the stage releases a microsatellite at the end of a high-strength conducting tether with a length of 20 km (12 miles). Using electrodynamic drag during several perigee passes in the highly elliptical GTO orbit, the tether is spun up. Using electrodynamic drag rather than electrodynamic propulsion for this means that no power supply is required, keeping the system as simple as possible (effectively some of the orbital energy of the stage is converted into rotational energy). In addition, the electric energy generated by the conducting tether can be used to power the system's electrical equipment. When the tip with the microsatellite reaches a velocity of 0.4 km per second (0.2 miles/s) on top of the system's orbital velocity, the satellite is released during a perigee pass. The extra speed will increase the apogee of the small spacecraft so much that it should be possible for it to reach the Moon! The baseline µTORQUE system, with a total mass of 20 kg (44 pounds), could put a 80-kg (175-pound) satellite into a lunar transfer orbit (Fig. 5.9).

The benefits of systems like the MXER and similar bolo momentum exchange tethers are that they enable large orbit changes with (near) zero propellant usage (unlike conventional rocket propulsion), offer short orbital transfer times (unlike solar electrical propulsion), and can be reused (unlike any type of propulsion requiring propellant). Moreover, they can be tested in space on dummy payloads before being employed to transfer real spacecraft.

An important limitation, however, is the required accuracy in the timing of the orbits of the target payloads and the tether, and the resulting short time available for rendezvous. If a catching opportunity is missed, another possibility may not come around for a long time. Another drawback is that any individual bolo can only send satellites into orbits with a similar inclination (angle with Earth's equator) as the tether system itself; a bolo in an equatorial orbit cannot send payloads into orbits over Earth's poles, for

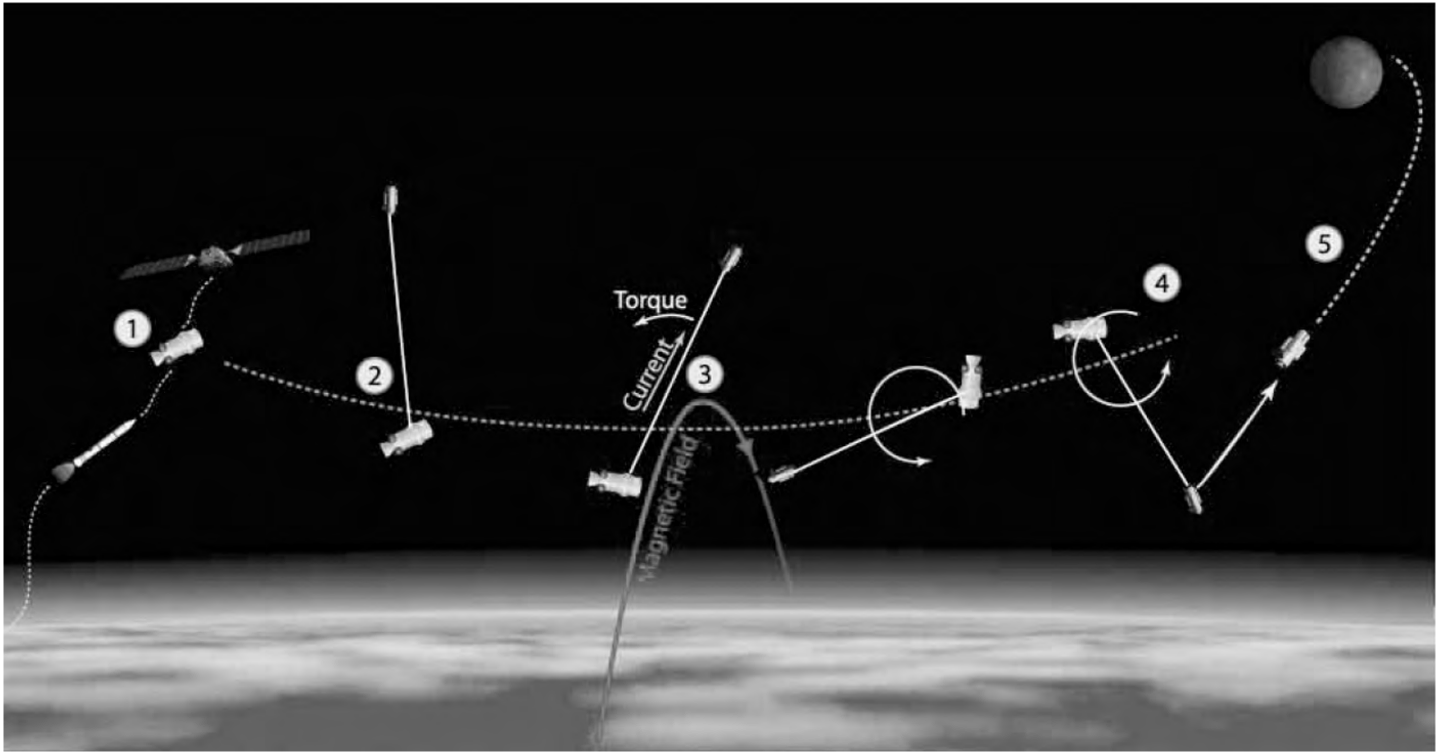


Figure 5.9: The various stages in the μTORQUE experiment. (Courtesy of Tethers Unlimited, Inc.)

example. Many bolo systems in various orbits may thus be needed to serve all possible satellite orbit requirements.

Complicated momentum exchange tether systems still have a long way to go before they can be considered operational technology. The costs of their development and deployment into space probably mean that they will be economical only if they are used for transferring many spacecraft on a regular basis. However, if we require continuous transportation of cargo or astronauts between a lunar base and Earth, tethers may prove to be a superior solution.

From the Ground Up

As we said before, an Earth-orbiting rotovator reaching down to the ground is probably unfeasible due to the drag of the atmosphere. However, you could use a bolo that only swings down to the top of the atmosphere in combination with a launch vehicle bringing payloads up to high altitude. Instead of going all the way into orbit, this rocket vehicle could follow a ballistic trajectory that would take it into space for only a short while. A satellite released by such a launcher at the top of its trajectory would of course also be suborbital, and thus fall back to Earth before circling the planet even once—unless the spacecraft would be picked up by the tip of the bolo tether at the bottom of its swing, at that moment exactly matching the speed of the satellite. The bolo would then sling the captured satellite to a higher altitude, giving it sufficient extra speed to stay in orbit as well.

Since the launcher as part of this system does not need to go into orbit, it could be relatively small, simple, and consequently less expensive than conventional satellite launchers. What's more, because of the lower demands on performance and less severe mass constraints, it is much less difficult to develop a suborbital reusable launcher than it is to design and build a fully orbital reusable vehicle. It would therefore be sensible to employ a reusable launcher in this concept. Such a vehicle could shortly hop up to the right altitude, release and pass on its payload to the tether docking device that is swinging by at a suborbital velocity, and then fly back to Earth to pick up another spacecraft to be launched. Such a combination of a suborbital reusable launcher and bolo may be more economical than a stand-alone orbital reusable spaceplane (see also Rocket Propulsion Limits and Limitations in Chapter 2).

A concept for a launcher-tether combination has been studied by Boeing, TUI, and the University of Maryland under the name Hypersonic Airplane Space Tether Orbital Launch System (HASTOL). It consists of a suborbital spaceplane, like the "hopper" mentioned earlier in Chapter 2, and a rotating tether with a grapple mechanism. The spaceplane reaches a velocity of 3.5 km/s (2.2 miles/s) at its maximum altitude of 100 km (60 miles), where it releases the payload. If the spaceplane takes off from the equator, Earth's rotation gives it a free additional velocity of about 0.5 km/s (0.3 miles/s). The total speed of the released satellite is thus about 4 km/s (2.5 miles/s). The spaceplane's maximum speed is equivalent to Mach 12 (i.e., 12 times the speed of sound), which is a very high velocity for an airplane, but not sufficiently fast to stay in orbit because that would require about twice that speed. The spaceplane thus follows a ballistic trajectory that brings it back to Earth. Immediately after release by the spaceplane, its payload is picked up by a homing and grappling system at the end of a long rotating tether then flying through its orbital perigee. This bolo lifts the payload further into space and provides the additional speed the satellite needs to stay in orbit.

Because the spaceplane needs to achieve only about half the speed required for an orbital vehicle, and because kinetic (movement) energy is equivalent to the square of the velocity, the amount of propellant it requires is about a fourth of what is needed for a conventional satellite launcher. To further decrease the amount of propellant that needs to be carried onboard, Boeing envisions equipping the hypersonic plane with engines that can use oxygen from the atmosphere for a large part of the flight.

The HASTOL study investigated four different types of bolo tethers to do the job. The first was a basic MXER rotating tether facility, composed of a central station (including power supply, a tether reel, avionics, and a large ballast mass), a 600-km-long (370-mile-long) tether, and a rendezvous/grappling system at the end of the cable. The tether could be made from already existing materials such as Spectra-2000, a fiber commercially used to make fishing line, and lined with conducting wire for orbit adjustments using electrodynamic propulsion. The bolo would need to be put in a slightly elliptical Earth orbit with a perigee altitude of 610 km (380 miles), giving its center of mass a perigee velocity of some 7.5 km/s (4.7 miles/s). The rotation of the tether, going round once every 18 minutes, would give its tip a velocity of 3.4 km/s (2.1 miles/s) with respect to the system's center of mass. Swinging backward, the tip's speed with respect to Earth would then be 7.5 – 3.4 = 4.1 km/s (2.5 miles/s)—just slow enough to be able to pick up the suborbital satellite released from the spaceplane at the same speed. Subjecting it to a mild acceleration of less than 2.5*g*, the rotating tether would then give its payload an additional 3.4 km/s (2.1 miles/s) of velocity—sufficient to keep it in orbit. The total mass of the tether needed to handle a 15,000-kg (33,000-pound) payload was calculated to be about 1,358,000 kg (2,994,000 pounds), while the station mass would be about 1,650,000 kg (3,638,000 pounds). The

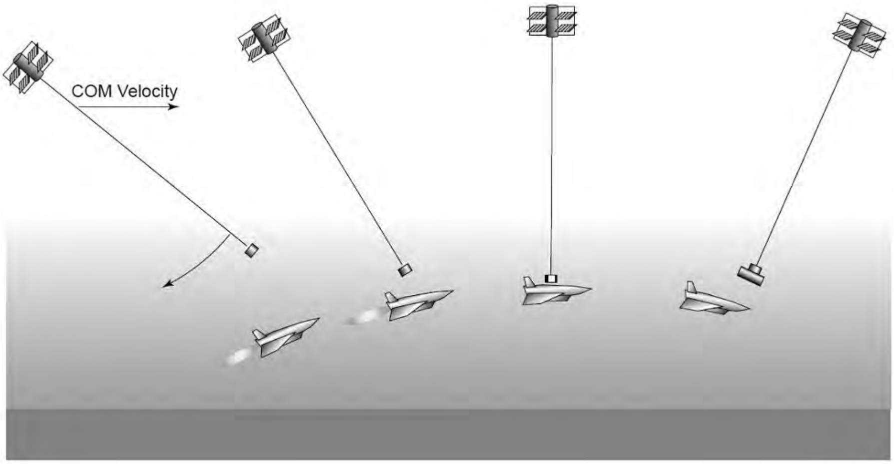


Figure 5.10: Rendezvous of a rotovator and a hypersonic spaceplane. (Courtesy of Tethers Unlimited, Inc.)

total bolo system to be put in orbit would thus have a mass of about 200 times the payload mass, obviously making many launches of sufficiently small sub-elements necessary (Fig. 5.10).

The mass of the tether itself forms about 45 percent of the total rotovator mass, and is directly related to the cable's thickness. The required thickness, in turn, is strongly related to the rotation speed of the rotovator; the faster the rotation, the thicker the tether needs to be to avoid breaking, and thus the higher its mass. It is like twirling a rope with a stone attached over your head, where the tension also increases with the rotation velocity. If you turn the rope slowly, you can use a thin rope, but if you increase the speed you will need a thicker cable or else the stone will break free. The mass of the HASTOL rotovator tether can thus be substantially decreased by making the system rotate slower. The problem is that when swinging down to pick up the spaceplane's payload, the tether tip will not have sufficient backward speed to match that of its target. In other words, from the point of view of the target payload the tether tip is moving away too fast in the direction the rotovator is orbiting around Earth.

Tethers Unlimited invented a smart solution to shortly decrease the tether tip velocity of such a too-slow rotating tether in the orbiting direction: aerobraking by temporarily increasing the aerodynamic drag of the tether tip, for example, by deploying panels or wings. The rest of the flexible tether will continue to rotate at the nominal speed, so for a short while there will be a bend at the end of the cable. After picking up the payload, however, the

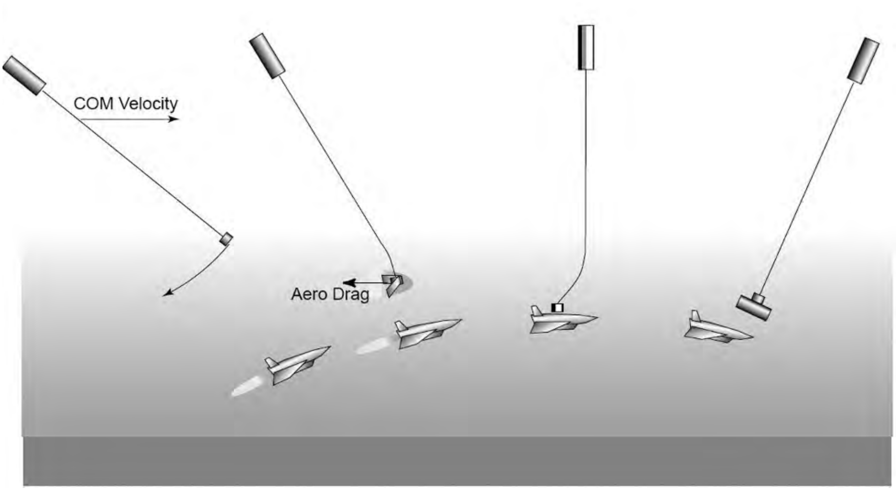


Figure 5.11: Rendezvous of a LIFTether and a hypersonic spaceplane. (Courtesy of Tethers Unlimited, Inc.)

tether quickly pulls taut and the tip will again follow the general rotation speed of the rotovator (Fig. 5.11).

Tethers Unlimited calculated that with this "LIFTether" concept the constant rotation speed could be reduced so that the tether tip's velocity would be 3.1 km/s (1.9 miles/s) instead of the 3.4 km/s (2.1 miles/s) needed for the normal rotovator. The 0.3 km/s (0.2 mile/s) difference in speed should enable the mass of the tether to drop to 526,400 kg (1,160 pounds)—a 60 percent reduction with respect to the normal rotovator tether, even with the bottom 20 km (12 miles) of tether made of titanium-coated silicon carbide to be able to handle the increased aerodynamic heat.

Another way to minimize the tether rotation rate and thereby minimize the tether mass is to use a two-stage tether, with a "second stage" spinning tether rotating at the end of a "first stage" spinning tether (for example, around a stiff pivot bearing supported on both ends by a split in the first tether). In this way the required total velocity of the second tether's tip can be achieved while each tether rotates at a much lower rate than required for a single-tether rotovator. The second tether must have two arms of equal mass extending both ways from the center of rotation for balance reasons. Moreover, the first tether will have to carry both the mass of the payload as well as that of the second tether, so the optimum mass distribution results in the first tether being much longer than a single arm of the second tether. For the basic rotovator the tether mass is about 90 times the payload mass it handles. Instead, for a two-staged tether where the required total tip velocity is split in nearly equal amounts over the two tethers, the combined mass of the cables could be as low as 20 times the payload mass. However, the downside is that the design and dynamics of such a two-stage tether is much more complicated than for a single-stage rotovator (Fig. 5.12).

A fourth type of bolo system studied for HASTOL was the Cardio-rotovator proposed by Robert L. Forward, which involves a very long tether in an elliptical orbit and rotating twice each orbit. Different from the rotovator and LIFTether, seen from Earth the Cardio-rotovator tether would be oriented below the central facility at the system's orbital apogee, and straight above it at perigee. The resulting trajectory of the tip of the tether is approximately heart-shaped, which lead to the peculiar name of the system. Because the Cardio-rotovator's orbital speed is at its minimum when passing apogee, the system's speed relative to the target payload is lower than for a normal rotovator picking up its cargo at perigee. As a result, the rotation speed of the Cardio-rotovator needed to match the target's velocity is some 0.5 km/s (0.3 miles/s) less than for the normal rotovator or LIFTether in a nearly circular orbit. The mass gained by the lower rotation and hence lower tension is of course partly lost due to the longer tether that is needed to be able to reach the target satellite from apogee (Fig. 5.13).

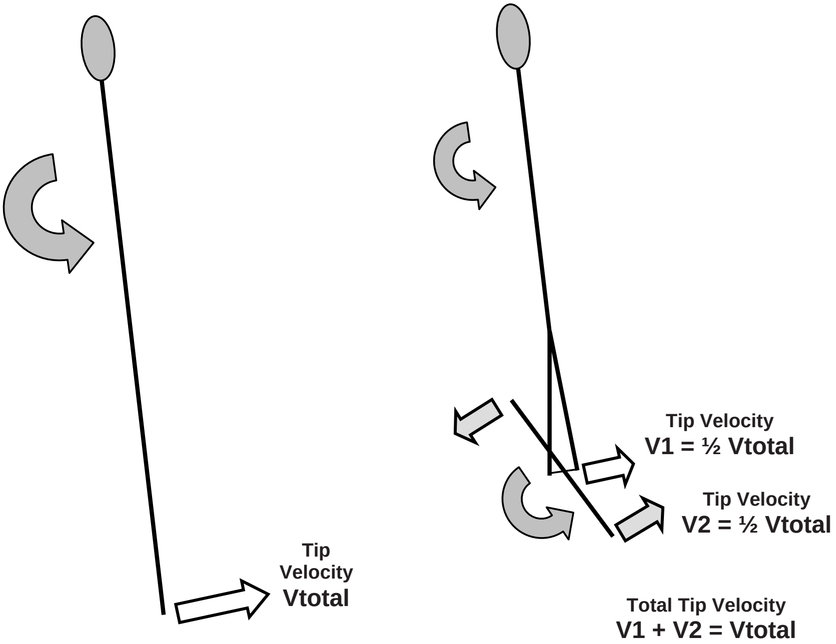


Figure 5.12: The principle of a two-stage tether that achieves the same total tip velocity as a normal, single-stage rotovator.

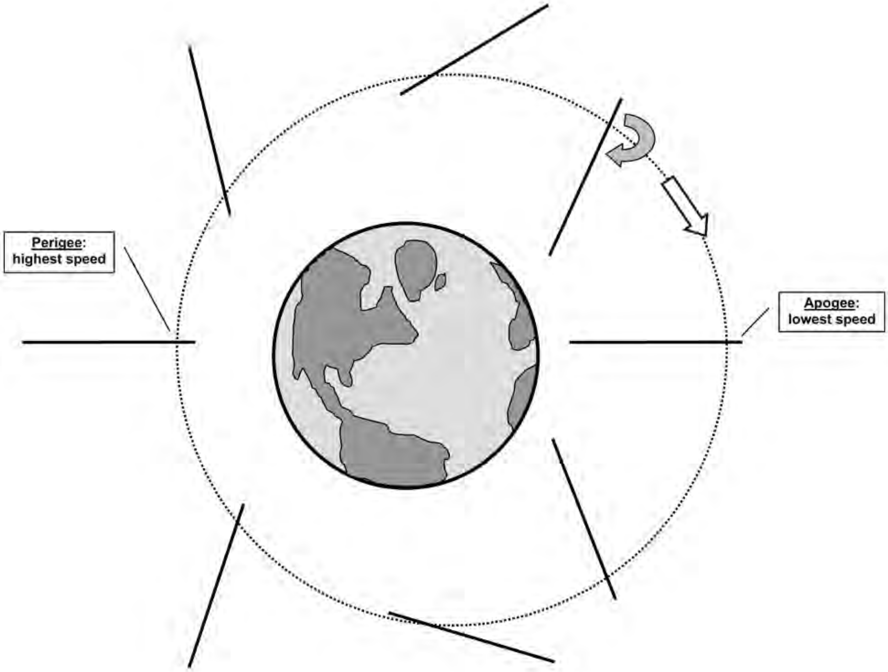


Figure 5.13: Orbit and rotation of a Cardio-rotovator.

However, the HASTOL study found two major problems with the Cardio-rotovator idea. The first is that picking up a mass at apogee decreases the total system's perigee altitude due to the momentum exchange principle and the orbital mechanics explained in Chapter 1 (see Orbits). For a normal rotovator, picking up a payload lowers its orbit altitude as well, but since it grabs its cargo at perigee the result is a decrease in apogee altitude. This is much less critical than the decrease in perigee altitude of the Cardio-rotovator, which can easily lead to an entry into Earth's atmosphere. TUI calculated that in order to avoid perturbing the orbit too much by picking up a suborbital payload, the Cardio-rotovator would need to have a mass that is 1000 to 2000 higher than the mass it picks up. Compared to the normal rotovator's mass of about 200 times that of the target payload mass, this is extremely high and completely negates the tether mass benefit of the slower rotation.

The second problem is that the change in orbit resulting from picking up cargo alters the orbital period of the Cardio-rotovator; its new, lower orbit would make it circle Earth in less time. As explained before, the rotational rate of the tether is not affected, meaning that the next time the system reaches apogee the tether will not be pointed straight down to Earth anymore. The rotational rate of the Cardio-rotovator could be aligned with the new orbit by reeling in part of the tether, which would make it rotate faster (just like a pirouetting ice-skater spinning faster when she tucks in her arms). However, any failure in this would make the tether enter the atmosphere, resulting in a loss of the system. TUI's conclusion was that employing a Cardio-rotovator for HASTOL is not a good solution.

The total mass of the orbital MXER tether in the HASTOL concept is high—about 200 times the mass of a single payload for the basic rotovator and still 145 times that mass for the LIFTether. This indicates that the HASTOL system makes sense economically only if it is used to launch many satellites on a regular basis. The basic rotovator starts to become more efficient than conventional rockets only after launching a minimum of 200 payloads of 15,000 kg; for any lower number of satellites, more rocket launches would be needed to put the rotovator in orbit than would be needed to launch the satellites directly! When we also take into account the development costs for the rotovator and the required spaceplane, the economic break-even point will be far over 200 payloads. The HASTOL concept thus suffers from the same catch-22 problem that haunts all reusable launcher concepts: their increased efficiency will make it possible to launch many more spacecraft for lower costs than conventional expendable rockets, but in order to become economically feasible they require a huge and stable satellite launch market. The relatively small satellite launch market of today does not warrant the huge investments needed to develop HASTOL into an operational system. Like MERITT and other large bolo concepts, HASTOL could enable large-scale cargo transportation from Earth to space and other planets, but requires much investment, development, and a considerably larger or at least fast growing launch market to become a reality.

Tether Propulsion

The MXER tethers use electrodynamic tether propulsion to move back to the right orbital altitude after slinging payloads into higher orbits. However, this novel means of propellantless propulsion can in principle be used on any spacecraft that spends at least part of its orbit below an altitude of 1000 km (600 miles) (Earth's magnetic field strength and the ionospheric density are too low higher up).

Tethers Unlimited is developing what they call the Microsatellite Propellantless Electrodynamic Tether (PET) Propulsion System (since the Greek letter stands for "micro" but is pronounced "mu," "PET" thus leads to the funny pronunciation "mu-pet"). It is designed to provide small satellites with a long-term propulsion capability for orbital maneuvering and stationkeeping in low Earth orbit. In addition, the tether system can also serve as a gravity-gradient attitude control element, stabilizing the satellite's attitude with respect to Earth. The mass, size, and power requirements of the PET Propulsion System depend on the size of the satellite and its mission, but TUI has developed a prototype sized for a 125-kg (276-pound) microsatellite. It is able to raise the altitude of the spacecraft's orbit from 350 to 700 km (220 to 440 miles) within 50 days.

An electrodynamic tether propulsion system could also be designed to be a stand-alone spacecraft, able to dock to other satellites and move those into other orbits. TUI's previously mentioned Debris Shepherd, a reusable tether propulsion spacecraft for de-orbiting space junk, is an example of such a system. In principle its design could also be used to intercept healthy satellites, change their orbits (altitude, eccentricity, inclination), and then undock and fly to another target.

A similar design is the Electrodynamic Delivery Express (EDDE), studied by the companies STAR and Tether Applications in collaboration with the U.S. Air Force Research Lab. It consists of two spacecraft connected by a conducting tether, but does not rely on gravity-gradient stabilization. Instead, it slowly spins around its center of mass (located in the middle of the tether) for increased attitude stability; as with a spinning top, the resulting gyroscopic effect keeps the rotational axis of the spinning system in the same direction.

However, the spin does introduce the problem that a current initially flowing upward through the tether with respect to Earth's magnetic field will be going downward half a rotation later. This results in a Lorentz force aimed forward for half a circle, then backward for the next half rotation, adding up to a zero net force. To ensure that the net electrodynamic Lorentz force keeps on pushing in the same direction, the direction of the current flowing through the tether has to be changed twice per rotation. A benefit of the spin is that with the proper varying of the current versus the tether orientation, the net thrust direction of the EDDE can be selected over a wide range. This is not possible with the always vertically orientated gravity-gradient stabilized tethers, where the thrust is always in either an eastern or a western direction (depending on whether the current flows up or down the tether).

Because of the periodically changing current direction, the EDDE must be able to collect and emit electrons at each end of the tether. Instead of one collector at each end, the EDDE has multiple collectors distributed over the entire tether, effectively resulting in a chain of individual but connected electrodynamic tethers. The benefit is that it increases the EDDE's capability to collect electrons from the ionosphere, raising the maximum operating altitude by allowing adequate current levels at lower plasma densities. It also makes it possible to vary the current levels and therefore the strength of the Lorentz force over the different parts of the tether. If this force is made stronger on one side of the EDDE tether (with respect to the rotational center) than on the other side, the rotational velocity of the tether will change. The rotation will speed up if the stronger force on one side acts in the same direction as the rotation, but slow down if the force acts in the other direction. The rotation rate of the EDDE tether can thus be accurately controlled.

NASA and TUI have also studied the possibility of using an electrodynamic tether for reboosting the ISS. As this huge station orbits Earth, it experiences a small but constant aerodynamic drag force from the thin upper reaches of Earth's atmosphere. This drag force needs to be counteracted to prevent the station from falling out of orbit like the Skylab station did in 1979. Regular flights of Russian Progress and European ATV spacecraft bring propellant to the station to fire its orbital maneuvering rocket engines and restore the orbit, and while they are docked these cargo vehicles also help out with their own engines. Without these orbit restoring boosts, the ISS would fall out of the sky after only several months. However, the reboosts cost lots of propellant, which needs to be brought from Earth and is expensive to launch. Instead, an electrodynamic tether propulsion system using excess power generated by the ISS solar panels could be used to constantly counteract the aerodynamic drag force without propellant. It could even raise the station's orbit. TUI estimates that their design could save up to $2 billion in propellant launch costs over 10 years of the station's operation.

In 2000 there was a plan to launch a similar electrodynamic propulsion tether to the Russian Mir space station. The station was falling out of orbit and desperately needed a reboost to keep it operational for commercial activities (including space tourism) then being planned by a company called MirCorp. The tether, named Firefly, was designed by Joe Carroll of Tether Applications, Inc., and Russian space station engineer Vladimir Syromyatnikov. It was built in the United States, and it was ready in 2000 to be delivered to Russia for launch aboard a Progress cargo spacecraft. Firefly, formally known as the Mir Electrodynamic Tether System (METS), consisted of a 150-kg (330-pound) assembly with a 5-km (3-mile) aluminum wire that was to be installed by cosmonauts on the end of the station's Kvant 2 module. A surplus spacewalk rocket backpack was to be attached to the end of the tether, to act as a countermass to help deployment and stability using the gravity gradient principle. A few kilowatts of electricity from Mir's solar arrays would be channeled through the tether to provide electrodynamic propulsion and slowly raise the station's orbit. However, there were problems winning approval from the U.S. State Department for an export license for the U.S.-designed tether under the International Traffic in Arms Regulations (ITAR). After more than a year, the State Department finally cleared export of the tether, but by then MirCorp had already run out of money and Russia had just announced that the Mir station would be de-orbited (it burned up in Earth's atmosphere in March 2001). Firefly was never launched.

Tethers Unlimited's most ambitious plan for the ISS is to use an electrodynamic tether to move the station's orbital inclination (the angle with which the orbit intersects Earth's equator). The current orbit of the ISS has an inclination of 51.6 degrees, which was necessary to enable Russian Soyuz rockets launched from Baikonur Cosmodrome to reach the station. The downside of this relatively high inclination is that it is not optimal for launches from NASA's Kennedy Space Center in Florida or Europe's Kourou launch site in French Guiana, which lie much closer to the equator than Baikonur. For flights from Kennedy Space Center, an orbit inclination of 28.5 degrees would be ideal, allowing the Space Shuttle or the future Ares I rocket to carry a maximum payload. The new Soyuz launch site built in French Guiana now makes it possible for Russian cargo vehicles to be launched from there, and with a launch pad upgrade also crewed Soyuz capsules could be launched from the European base. Thus, it would no longer be necessary to facilitate ISS launches from Baikonur, and the ISS's orbital inclination could be lowered to maximize the payload mass capabilities for Kennedy Space Center and Kourou launches.

However, changing the orbit inclination of the ISS from 51.6 to 28.5 degrees with conventional rocket engines would require a mass of propellant nearly as large as the total mass of the whole station itself. All this propellant would need to be launched from Earth, making the whole idea economically unviable; the launch mass benefits gained from the inclination change would not outweigh the costs for first launching all the necessary inclination change propellant. Electrical rocket propulsion systems (ion engines) could do the job for much less propellant, but would require enormous power supplies to provide a reasonable level of thrust. An electrodynamic tether with a modest power source could change the ISS's inclination without propellant. TUI proposes using a 50-km (30-mile) conducting tether and spinning flywheels to store energy generated by the ISS's large solar arrays. TUI projects that this system could move the station's orbit to the ideal inclination in 4 years.

Yet there are currently no plans to implement any type of tether propulsion system on the ISS, due to the required investments and the previously described safety issues related to long tethers in the vicinity of crewed space stations. NASA is moving its attention and the bulk of its crewed spaceflight budgets to its new lunar exploration plans, and the future of the ISS after 2015 is uncertain. It is therefore unlikely that there will be money and time available for developing tether applications for the space station. Moreover, there are currently no firm plans to launch crewed Soyuz rockets from Kourou (which would require expensive additions to the current launch pad), and as long as Russia needs access to the ISS from its Baikonur launch site, moving the station's inclination is out of the question.

For interplanetary travel, electrodynamic propulsion tethers could be embedded into solar sails like the spokes in a bicycle wheel, thus combining two very innovative space technologies. The solar sail would be used to propel the spacecraft through space, and the electrodynamic tethers to generate propulsion for maneuvering the spacecraft in orbit around a planet with a strong magnetic field (like the Earth and Jupiter). The tether system could further be used to generate electrical power for the spacecraft while slowing down in the planet's magnetic field using the electrodynamic drag principle.

Jupiter

The Jovian system, encompassing the giant planet Jupiter and its diverse collection of moons, is currently a popular target for robotic exploration in both NASA and European Space Agency plans. Jupiter itself is the largest planet in the solar system, with a maximum diameter 11 times that of Earth. Even though the planet could contain over 1300 Earths, its mass is only 318 times that of our world because Jupiter consists primarily of the light elements hydrogen (about 86 percent) and helium (about 14 percent). In the uppermost layers of the atmosphere these exist in a gaseous state, but deeper down the pressures are so high that they behave as fluids and solids. The colorful cloud bands circling the planet consist of various compounds of ammonia and hydrogen sulfide. Jupiter has four large moons, which are all very different and at least as interesting as any of the planets. Callisto has a densely cratered surface of dark, muddy ice that has probably remained virtually unchanged since the birth of the solar system. Ganymede is larger than our own moon, and even larger than the planet Mercury. It has mountains as tall and wide as those on Earth. Io is covered with layers of white, red, yellow, and black sulfuric material that erupts from active, but very cold, volcanoes. Icy Europa is perhaps the most intriguing of Jupiter's moons. Slightly smaller than our own moon, it is covered with a smooth icecap that completely envelops it. We now think that the ice is several kilometers thick, but it hides a vast water ocean below it.

The gravity level around a planet is a function of the distance to the center of the planet; the further away, the lower it gets. That means that the side of a moon facing a planet is attracted slightly more strongly than the side facing away from it. As Io spins on its axis, it is distorted by Jupiter's tidal forces. This causes heating, which increases the temperature of the sulfur-rich rocks deep inside Io, leading to the release of sulfurous gases (it is a bit like heating up a ball of clay by kneading). The gases exit the moon through the volcanoes, spewing far into space. The gas often even escapes the relatively low gravity of Io, going into orbit and getting captured and charged by Jupiter's powerful magnetic field. These energetic gas particles are the main cause of the high levels of radiation around Jupiter. Just like the interior of Io, the interior of Europa must also be heated by Jupiter's tidal flexing, and is therefore probably liquid. That means Europa may harbor a giant water ocean, which might even contain some form of life. Callisto and Ganymede probably also contain water oceans, but Europa remains the most promising; unlike on its sister moons, its water is probably not sandwiched between ice layers but in direct contact with the rocky mantle, allowing life-supporting nutrients to leach directly into the ocean. All the ingredients for life, being liquid water, energy, and chemical building blocks such as carbon, oxygen, hydrogen, and nitrogen, may thus be available beneath Europa's icy cover.

Jupiter has a very strong magnetic field. The unfortunate part about this is that it captures and electrically charges lots of particles ejected by its own moon Io and also from the Sun, which results in very high radiation levels. When the Pioneer 10 space probe made its closed approach to Jupiter in 1973, it had to endure some 500 times the amount of radiation that would be instantaneously deadly to humans. However, the giant planet's powerful magnetic field may also be an ideal place for electrodynamic tether applications. In both absolute and relative terms, Jupiter's magnetized ionosphere full of charged particles extends much deeper into space than Earth's ionosphere does. At our planet's geostationary altitude of 36,000 km (22,000 miles), electrodynamic tethers cannot be used due to the low plasma density. However, the ionospheric plasma at Jupiter's stationary orbit altitude of 88,500 km (55,000 miles, with respect to the top of the clouds) is still sufficiently dense to allow the application of electrodynamic drag and propulsion.

Jupiter's magnetic field and therefore its ionosphere rotate together with the planet itself, locked as they are to the core of the planet. This means that at its stationary orbit altitude a satellite remains motionless with respect to the magnetized plasma and no electrodynamic force is produced. If a spacecraft with a conducting tether descends to a lower altitude, its orbital speed will increase and thus become higher than that of the plasma. Just like on Earth, the tether will then generate an electrical current and an electrodynamic drag force; power is generated at the expense of orbital energy and therefore altitude.

Because the plasma is locked to the planet's magnetosphere and therefore the rotation of the planet itself, the further out it is, the faster it moves—just like how parts of a wheel are moving faster the closer to the rim they are. A satellite's speed, however, decreases when orbiting at a higher altitude. As a result, when a tether satellite circles the planet above the stationary orbit altitude, it will move slower than the plasma it flies through. The difference in speed between the satellite and the plasma will again result in power generation and hence an electrodynamic drag force, but this time that force acts in the same direction as the satellite's orbital speed. The "drag" force is thus, in effect, a propulsive force for the satellite with respect to the planet itself. At Jupiter, a tether can thus generate power and increase its velocity at the same time. At Earth this is not possible because its ionosphere does not extend beyond geostationary orbit; electrodynamic propulsion is then only possible at lower altitudes, by generating a current in the right direction through the use of a power source like solar arrays or batteries (Fig. 5.14).

The combined propulsion and power generation possible at Jupiter does not mean that energy is somehow obtained for free; there is no magic involved. The Lorentz force that propels the tether also acts on the plasma, pushing to slow down the ionospheric plasma and the rotating magnetosphere it is locked onto. Since this magnetic field is tied to the metallic core of Jupiter itself, the Lorentz force effectively slows down the planet's rotation. The energy that the tether satellite builds up in terms of velocity and electrical power is thus deducted from the rotational energy of Jupiter. However, since the mass and therefore rotational energy of the planet is so vast, the effect of the energy "drain" is completely negligible.

Electrodynamic drag could be applied to slow down an incoming space probe that would otherwise fly past Jupiter. A visiting spacecraft launched from Earth, and deploying a conducting tether some tens of kilometers in length when flying below the planet's stationary orbit, could thus be slowed down sufficiently to fall into a highly elongated orbit around Jupiter. Turning the tether on (by closing the electrical connection between the electron collecting anode and electron expelling cathode) when moving below stationary orbit altitude and turning it off elsewhere, the spacecraft could be further slowed down. As the deceleration would constantly occur near the point closest to Jupiter (the periapsis), the result would also be a more

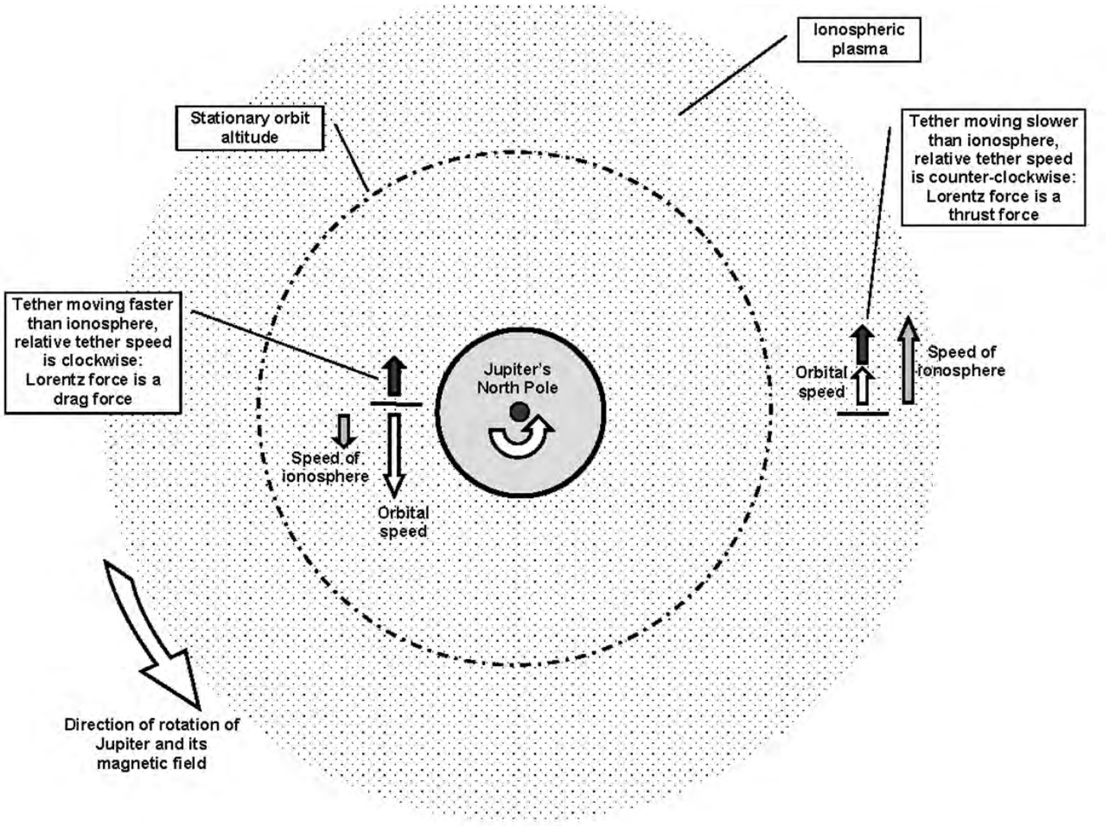


Figure 5.14: Whether the Lorentz force decelerates or speeds up an electrodynamic tether in orbit around Jupiter depends on whether it orbits below or above the stationary orbit.

circular orbit (as explained in section Orbits in Chapter 1). Normally such orbital braking maneuvers are performed by rocket propulsion systems, at the expense of onboard propellant and thus mass to be carried along. At Mars aerobraking can be used, whereby a spacecraft makes short dips into the higher atmosphere to use the aerodynamic drag to slow down. However, at Jupiter the radiation levels close to the planet are extremely high and would damage sensitive onboard equipment if not protected by heavy shielding. In addition the properties of Jupiter's upper layers are not well known, so predictions of aerodynamic drag are inaccurate and could result in a spacecraft burning up rather than gently slowing down.

At appropriate moments, by turning the tether on below the stationary orbit (resulting in electromagnetic drag) or above it (for electromagnetic thrust), the spacecraft's orbit altitude could be changed at will. This could help tune the orbit to those of the various moons, to enable more frequent visits than is currently possible using rocket propulsion and moon flyby maneuvers. It even may be possible to return a tether spacecraft with a captured sample of Jupiter's ionospheric plasma to Earth, by using electrodynamic thrust to increase the apoapsis altitude until escape velocity is reached. Using traditional rocket systems, such a probe would require lots of propellant, resulting in a very large, heavy, and therefore costly spacecraft.

Cleaning Up the Belts

The possibility of removing dangerous charged particles from the vicinity of Earth was mentioned in Chapter 1 (see Electrostatic Tethers). As stated, the energetic particles in Earth's Van Allen belts steadily degrade spacecraft electronics, sensitive optical equipment, solar arrays, and human body cells because they break the chemical bonds within the materials they consist of. They also cause localized charge effects that can disrupt and even damage electronic equipment. The high radiation fluxes in the Van Allen belts thus limit long-duration crewed missions to orbits below altitudes of about 1200 km (750 miles). Moreover, spacecraft and people passing through the belts on their way to the Moon or other planets have to minimize their transit time to limit the damage. This is particularly problematic for spacecraft utilizing solar electric propulsion, because the efficient but low thrust means that they take a long time to spiral through the belts up to higher and safer orbits. Especially the solar cells on which the electric propulsion depends degrade fast, meaning satellites have to start out their journey with considerably overdimensioned solar arrays. Consequently, the radiation belts form one of the primary obstacles that prevent solar electric propulsion from being used in propulsion stages for moving satellites from low Earth orbit to geosynchronous orbit (GEO).

Less trapped energetic particles in the Van Allen radiation belts surrounding Earth thus means increased safety for crewed missions and a higher reliability and lifetime for spacecraft in Earth orbit, as well as increased potential for solar electric propulsion. TUI is studying a tether concept for cleaning up the Van Allen belts; it is called ElectroStatic Radiation Belt Remediation (earlier it was called the High-Voltage Orbiting Long Tether [HiVOLT] System). It utilizes lightweight conducting tethers, each many tens of kilometers in length, that are deployed into orbits that bring them into the radiation belts. The tethers automatically assume a vertical orientation due to the gravity-gradient forces, and thus align themselves perpendicular to Earth's magnetic field lines (imaginary lines along which the magnetic field strength is the same, and which run from pole to pole). Trapped radiation particles spiral along geomagnetic field lines, so with the tethers being perpendicular to these field lines they are able to encounter as many particles as possible. When the tethers are charged to a large negative voltage, an intense electromagnetic field is created around them. This field will disrupt the spiraling path of the charged particles that come near, deflecting them into other orbits. The deflection process is random, so many particles will have their paths changed but nevertheless continue to be imprisoned inside the cage formed by Earth's magnetic field lines. However, some of the particles will be sent on new courses that bring them out of the radiation belts and into Earth's atmosphere. Over time, the tethers can remove sufficient numbers of particles so that the radiation levels inside the belts are significantly decreased (Fig. 5.15).

Tethers Unlimited did investigate the potential effects of the increased rain of charged particles into the atmosphere, and concluded that these will be very mild and short-lived, comparable to the impact of a very weak solar storm (an event during which the Sun expels an increased amount of charged particles).

To enhance the effectiveness of the electrostatic tether, a series of parallel wires can be used; the wires will automatically stay at a distance and parallel to each other due to the electromagnetic repulsion force between them, an effect similar to how two magnets can push each other away (the force in the wires is a result of the current running through them in the same direction, each creating an electromagnetic field around the wire as well as a Lorentz force reacting on the electromagnetic fields of the other wires).

According to TUI, its system has the potential to reduce the number of particles with harmful levels of energy in the inner electron belt to only a

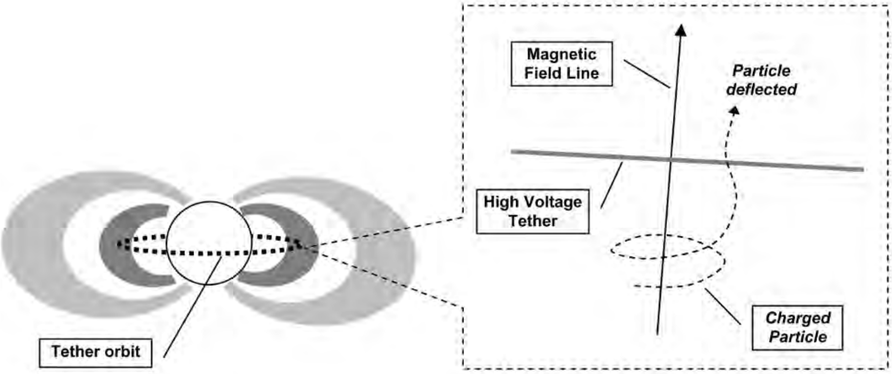


Figure 5.15: A charged particle trapped in the inner radiation belt deflected by a charged electrostatic tether.

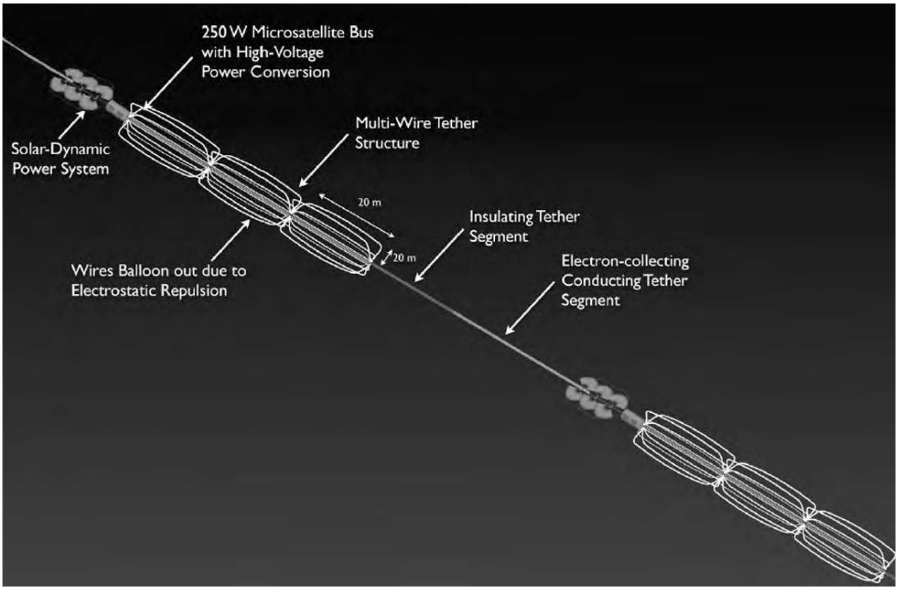


Figure 5.16: TUI's concept for a modular electrostatic tether to clean up the Earth's radiation belts. (Courtesy of Tethers Unlimited, Inc.)

couple of percent of its natural levels within a year. For that, the system requires 24 tethers, each with a length of about 100 km (60 miles) and a 5-kilowatt power supply, to be put into orbit. The individual tethers could be built up from several relatively short tether modules, connected to each other like train wagons. Each module would consist of first a short length of conducting tether acting as an electron-collecting anode, a small satellite bus with a solar power collection system and a tether deployment mechanism, a long multi-wire conducting part serving as the actual electrostatic structure, and finally a segment of nonconducting cable to insulate each module from the next. The wires could be very thin, resulting in a total mass of only a couple hundred kilograms for a 100-km-long (60-mile-long) tether system. The idea could be proven by a small tether satellite equipped with a several kilometer long tether and sensors able to measure the increased precipitation of energetic electrons into the upper atmosphere (Fig. 5.16).

An even more ambitious plan involves the partial remediation of Jupiter's vast and powerful radiation belts. With 100 tether spacecraft, TUI says it should be possible to dramatically lower the radiation levels in a narrow band around one of the moons. That would help make robotic and possibly even human exploration of Europa possible.

Space Elevators

6

The most difficult part of spaceflight is getting off the ground and into orbit. Mankind has long dreamed of easy access to the heavens. It is even the idea behind the Tower of Babel, as in the Book of Genesis the descendants of Noah say, “Let us build us a city and a tower, whose top may reach into heaven.” The use of a space elevator to lift things from Earth into orbit is by far the most daring, complicated, and challenging application of tether technology, but also the one with potentially the highest impact and most benefits. In Chapter 1 we discussed the basic principle behind the space elevator concept. Now we get a closer look at this fascinating idea.

Who Wants a Space Elevator?

As described in Chapter 2, it takes a large and very expensive rocket to launch even a relatively small satellite. The launch is also often the most risky part of a space mission; even today a commercial launcher has typically between a 1 and 3 percent chance of blowing up, depending on the type and reliability of the launcher. This may not seem to be too bad, but if one in a hundred aircraft would come falling from the sky every day, the ground would be littered with burning aircraft wreckage. Economic, safe, and routine air travel would be impossible. Something radically new is needed to provide the reliable, low-cost access to space that spaceflight engineers, scientists, and other enthusiasts have been dreaming about for the last hundred years. Constructing a space elevator will undoubtedly be an extremely difficult and expensive endeavor, but if the gains outweigh the investments it will be worth doing.

What are the benefits we could expect from an operational space elevator? The 1966 study of the engineers of the Scripps Institute of Oceanography led by John Isaacs stated:

M. van Pelt, *Space Tethers and Space Elevators*, DOI: 10.1007/978-0-387-76556-3_6,

> In addition to their use for launching materials into space, such installations could support laboratories for observation of conditions in space at high altitudes; they could resupply energy or materials to satellites or spacecraft, collect energy or materials from space and the high atmosphere, support very tall structures on the earth's surface, and others. There is no immediate limit to the total mass that could be retained near the one-day orbit by such a cable.

The primary use of a space elevator will probably be the delivery of satellites into space. Not taking into account the initial cost of development and construction, a space elevator could dramatically lower the recurring cost of launching a satellite. In terms of electrical power required to transport cargo up a space elevator, the cost could be less than ten dollars per kilogram. This is tiny compared to the current price for a launch, which ranges from $5000 to $10,000 per kilogram. It is likely that for each satellite an amortization fee will be added to the bare launch price, in order to pay back the investments for building the space elevator. In addition, there will be costs associated with the operation and maintenance of the space elevator system. However, if enough satellites are launched, the price per launch can still be much lower than is currently the case. In addition, the cost for a space elevator may be shared with clients for other applications, such as microgravity industries and space tourism.

It is very likely that the demand for spacecraft launches will increase dramatically once prices for putting them in orbit drop significantly; more and more organizations and countries will be able to afford space missions, and more people will find ways to make money from the use of satellites and space applications. Moreover, for similar budgets now required to launch a couple of interplanetary probes per decade, we could send out a steady stream of continually improved spacecraft to investigate other planets. Elevator-deployed satellites could also be much larger and therefore more capable than now, because they could be transported up in sufficiently small elements that are subsequently assembled at the orbital station. Extending this concept will make it possible to construct large-scale systems in orbit from parts prefabricated on Earth and transported into space by the elevator. These could include giant radio telescopes, solar collectors for generating power and transmitting it to Earth, and large crewed interplanetary exploration vehicles.

Instead of replacing entire satellites because of relatively small but important malfunctions or depletion of attitude control propellant, geostationary satellites could be moved back to the space elevator station for repair, refueling, or even modification. Currently, maintenance on satellites happens very rarely, due to the high cost for crewed space missions (the Space Shuttle has only occasionally been used for orbital repair work, most notably on the Hubble Space Telescope). Spacecraft can also be entirely returned to Earth using the space elevator. Space probes normally require heat shields and parachutes to reenter Earth's atmosphere and make a soft landing. If they could dock to the space elevator in space and be gently transported down, there would be no need for heavy reentry and parachute systems, and it would also be much easier to reuse the spacecraft afterward (heat shields can normally be used only once, and even the reusable tiles of the Space Shuttle require a lot of repair after every flight).

Another potentially important application is industrial manufacturing inside the main station. The microgravity conditions there would allow new types of alloys of metals that do not mix under gravity conditions due to differences in density (on Earth, lighter melted metals float on top of denser materials). Also interesting is the growth of crystals that are larger and more pure than those manufactured on Earth, where buoyancy-driven convection in liquids has a disturbing influence. Such crystals have many uses in medicine and electronics. Despite high expectations in the 1970s and 1980s, commercial microgravity manufacturing has never taken off because of the high cost for launching raw materials into space, astronaut labor, and return of products to Earth. However, a space elevator could make space industries profitable.

The geostationary point could also be the location for a space hotel, providing an affordable and fascinating new holiday destination. Guests could enjoy weightlessness and observe Earth from space, which they would be able to see as a complete globe from the geostationary point at an altitude of 36,000 km (22,000 miles). The trip up the elevator inside a suitably comfortable cabin would be long, but an adventure in itself. Space tourists would slowly see the horizon start to curve and finally form a complete circle. At the same time they would slowly lose weight, reaching microgravity conditions at the geostationary point. Space hotels and other crewed facilities could alternatively be built somewhat below or above the geostationary point, as a tiny level of gravity would facilitate sleeping, washing, and eating, and may alleviate typical physiological microgravity problems such as space sickness, muscle atrophy, and bone loss. Below the geostationary point people would stand with their feet pointing toward Earth, as gravity would be slightly higher than the compensating centrifugal force. However, above the geostationary point the centrifugal force is stronger; when people stand, the Earth would consequently always be straight over their head.

As the space elevator always hangs above the same part of Earth, it provides an excellent viewpoint for Earth observation instruments. The big benefit with respect to geostationary satellites is that the instruments in principle can be placed anywhere along the space elevator ribbon, making it possible to put them close to the ground and thus increase their resolution (as the same instrument will be able to see more details than from geosynchronous orbit [GEO] altitude). Instruments placed at intervals on the ribbon will also enable detailed studies of Earth's upper atmosphere and near-space environment.

Apart from the applications that can already be identified now, there will be many that we cannot yet foresee—possibilities that people will only think of once the space elevator really exists. As happened before with airplanes (originally only used for recreation), computers (initially only intended to make complicated calculations), and most notably the Internet, a space elevator will create its own applications (Fig. 6.1)

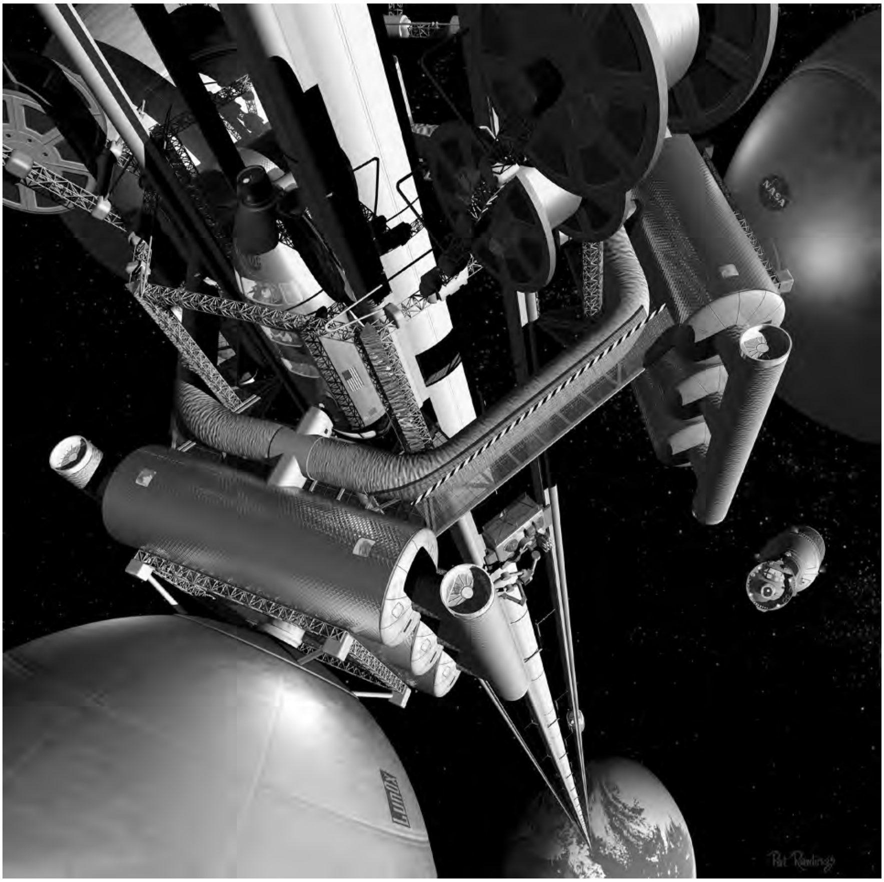


Figure 6.1: Artist's impression of the view from a space elevator geosynchronous orbit (GEO) station, looking down the length of the cable toward Earth. (Courtesy of NASA's Marshall Space Flight Center and Pat Rawling.)

Some people are so confident that we will be able to build a space elevator in the near future that they are already trying to make a business out of it. The LiftPort Group, founded in April 2003, is a group of small companies in the United States dedicated to building a space elevator. Their goal is "to provide the world a mass transportation system to open up the vast market opportunities that exist in space, many of which haven't even been imagined yet, to even the smallest entrepreneur." The group focuses on developing the hardware of the space elevator, including such fields as carbon nanotube production and climber/lifter technology, and challenges such as how to connect the space elevator tether to Earth. The group's motto is "Change the world or go home." While developing space elevator equipment, LiftPort is earning income on related technology, such as balloon-borne observation and telecommunication platforms based on the high-altitude balloons they use to raise long tethers for climber/lifter tests.

The space elevator concept is also serious business to the professionals and space enthusiasts gathered for the International Conference on the Space Elevator in 2002, 2003, 2004, and 2008 in the United States, and in 2007 for the First European Workshop on Space Elevator Climber and Tether Design in Luxembourg. The purpose of these conferences is "to bring together scientists, engineers, businessmen, economists, educators, financiers, writers, students, and others interested in the Space Elevator for wide-ranging papers and discussion sessions," according to the announcement for the 2008 conference on the Microsoft campus in Redmond, Washington. On the other side of the world, the Japan Space Elevator Association (JSEA) is seriously studying and promoting the concept. The group hosted a space elevator conference in Japan in 2008 and endeavors to launch its own space elevator games in 2009. Clearly the space elevator is moving out of the realm of pure science fiction.

Building a Beanstalk

The idea of starting the construction of a space elevator from geostationary orbit, as proposed in 1960 by Yuri Artsutanov, is still the baseline for current space elevator plans. However, important improvements have recently been proposed by Bradley Edwards, a pioneer in the field of space elevator engineering. Working on NASA grants (a total of $570,000 by 2003) and leading a research staff of 70 people at the Institute for Scientific Research (ISR) in West Virginia, he has developed a more refined strategy. In his plan, construction begins with the launch of a satellite carrying a spool of ribbon tether, paper-thin and tapered from about a third of a meter (one foot) wide at GEO to some 14 cm (5 inches) at Earth's surface. This tether would have to be made of a revolutionary, extremely strong, and not-yet-existing material. The ribbon will likely be based on strings of carbon nanotubes held together by an epoxy matrix. The use of anything else would result in an extremely heavy and thick cable, requiring thousands of rocket launches to put up. Edwards is confident that the ongoing development of nanotube materials will eventually result in the tensile strength, with a safety factor of two, of 130 gigapascals that he needs for his design; 130 gigapascals translates to a load of 1,300,000 kilogram per square centimeter (18,500,000 pounds per square inch). Using a cable with such an incredible tensile strength, it would be possible to vertically suspend the entire, fully loaded, 83,000 metric ton (183,000,000 pounds) aircraft carrier U.S.S. John F. Kennedy on a cable with a diameter of just under 10 cm (4 inches)! In comparison, the tensile strength of steel is only 42,000 kilogram per square centimeter (93,000 pound per square inch), or just over 3 percent of what would be needed for a space elevator (for more on this topic, see Cable Material in Chapter 7).

The tether deployer satellite will be rather large and heavy; in Edwards's estimation over 80 metric tons (175,000 pounds) in mass, including propellant to move it from a low Earth orbit to GEO. A Space Shuttle can put about 24 metric tons (53,000 pounds) in a low orbit, so at least the equivalent of four shuttle launches and some in-orbit assembly would be required to put a complete deployer in space. More flights are probably required if the volume restrictions are taken into account. On the other hand, the new Ares V launcher NASA hopes to have operational by 2020 should be able to lift 125 metric tons (275,000 pounds) into a low Earth orbit. A single launch of this huge rocket may thus suffice.

Once assembled in space and thrust into geostationary orbit, Edwards's satellite would start unwinding a single tether ribbon. Some velocity will have to be imparted to it to start the deployment, but once a couple of kilometers are out, gravity-gradient forces will pull the rest of the tether away. In reaction to the lowering of the cable and according to the principle of momentum exchange, the satellite with the spool will go upward. This automatically ensures that the system's center of mass remains at the right, GEO, altitude (or seen in another way, the satellite goes up because conservation of momentum will ensure that the total system's center of mass will remain at the same altitude). As long as it keeps on deploying tether, the satellite will continue to move further up to higher altitudes.

In earlier concepts like that of Artsutanov, two cables were usually envisioned to be deployed: one downward and one upward. They would be unrolled simultaneously so as to keep the deploying spacecraft in GEO. In the deployment scheme of Edwards, only one cable is rolled out, and the

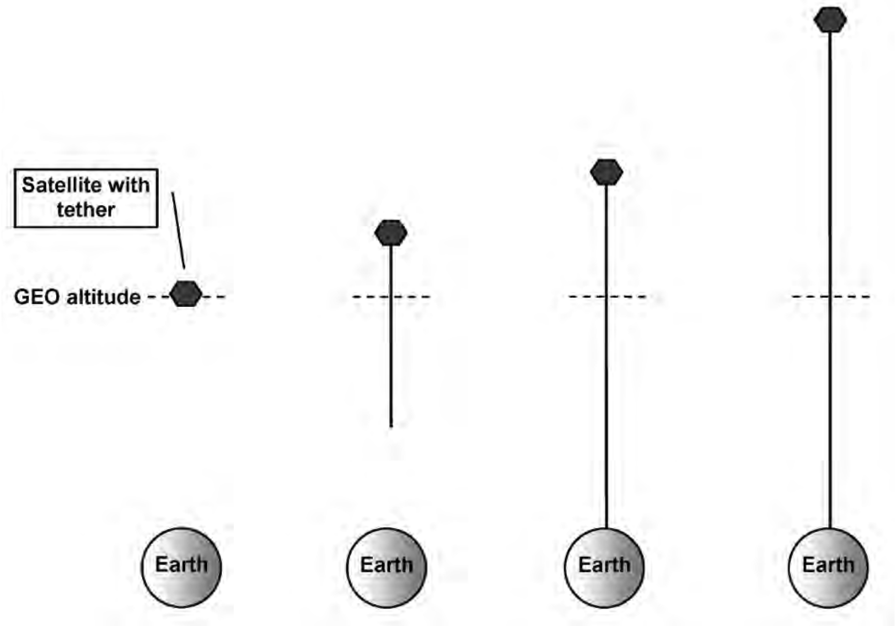


Figure 6.2: Deployment of an initial space elevator cable according to the plan of Bradley Edwards.

deployer satellite is allowed to drift upward to later act as the initial countermass. In comparison to the dual-cable deployment of Artsutanov, this single-cable concept should significantly simplify space elevator construction.

When the tether in Edwards's concept eventually reaches the surface at the equator, it is tied to Earth and the first space elevator link is complete. The satellite will however keep on deploying tether, drifting further outward until it reaches an altitude of some 100,000 kilometers (62,000 miles), over a fourth of the distance to the moon. There it will stay to act as the required countermass, keeping the cable taut (Fig. 6.2).

The single cable will still be relatively weak and vulnerable, but sufficiently strong to carry the first mechanical climber/lifter. This machine is sent up from Earth and, while ascending, deploys and attaches a second tether alongside the first one. A second, maybe even heavier climber carrying a thicker ribbon can now be sent up to deploy and attach a third parallel cable string. This process is repeated over 200 times until a sufficiently strong space elevator is formed, allowing heavy cargo climbers to ascend into space. The completed cable will be tapered, with its largest cross section at GEO, where tension in the space elevator will be highest. At the Earth's surface, the pull on the tether will be rather small—just enough to prevent the whole system from coming down due to the mass of a climber starting its ascent.

The increasing mass of the growing cable reaching down to Earth has to be compensated for, to prevent the space elevator from being pulled down. A solution could be lengthening the cable above the GEO point, which increases the rotational velocity of the end mass and thus results in a stronger centrifugal force on the cable (the end mass will travel a wider circle while still making one round in 24 hours, which means it will have a higher speed). However, it would be more practical to add mass to the original deployment satellite acting as countermass at the top of the tether. That could be done by parking the cable deploying climbers there after they have done their job, as Edwards suggests. In his cost estimates, the effective cost of the delays in upgoing transportation due to the time required to bring climbers back down on the same single cable is higher than the cost for new climbers. If the economic balance turns out to be different, it may be more efficient and less expensive to transport cheap material like stones or sand from Earth to the end point with reusable cargo climbers.

In science-fiction stories and even technical descriptions of space elevators, the countermass is frequently provided by an asteroid, which is often also mined to supply the raw materials needed for the construction of the cables. However, capturing a Sun-orbiting asteroid and using it in Earth orbit as the starting point for a space elevator is way beyond our current technical capabilities. It would involve somehow landing powerful propulsion systems on an asteroid and using them to change its orbit. A series of carefully choreographed planetary flybys would probably also be needed to sufficiently modify the asteroid's trajectory and put it in orbit around Earth. The employed method would need to have a very high level of accuracy, to avoid an asteroid impact catastrophe (such as the dinosaurs experienced). Capturing asteroids to build space elevators means making one revolutionary technical development (the elevator) dependent on yet another one (capturing asteroids), which is generally not solid engineering practice.

A space elevator able to handle 20-metric-ton (44,000-pound) climbers, taking into account Edwards's assumptions on the revolutionary tether material, would have a total mass of 1600 metric tons (3,500,000 pounds)—1000 metric tons (2,200,000 pounds) of tether and another 600 metric tons (1,300,000 pounds) of counterweight. This does not appear to be a ridiculous amount of material to put in orbit, as the International Space Station has a mass of about 500 metric tons (1,100,000 pounds).

A completed space elevator could be used to build more of them, because the easy access to space it provides would simplify sending up new space elevator deployer satellites. The amount of time and money required to construct them would drop for each subsequent elevator, eventually resulting in large-scale, regular and affordable transportation to space. In fact, the construction of a second space elevator is likely to be the first thing the initial system will be used for, to avoid having to start all over again if the original space elevator is destroyed for whatever reason.

Instead of using climbers to add lines to the initial cable, alternative ideas have been developed involving the lifting of additional tethers using a reel mechanism on the GEO satellite. Similar to the climber concept, a potential problem with this approach is that it would pull itself out of orbit if the mass of the uploaded tether is too high with respect to the centrifugal force provided by the countermass. A solution could be to first pull up a very thin, lightweight tether and then use that to haul up additional countermass material. The cable could subsequently be pulled back down to Earth to lift up more countermass and additional parallel tethers to reinforce the space elevator. An issue with this scheme is that if the reeling mechanism on the satellite fails, the whole space elevator construction process breaks down. Climbers instead are easily replaceable. On the other hand, a benefit is that instead of hundreds of climbers, potentially only a single satellite reel mechanism is required.

An important decision in the development of any space elevator is where to connect it to Earth—that is, the location of the anchoring point. As we have seen in Chapter 1, this point has to be located on the equator. A location on land in South America or Africa seems to be a logical choice. However, using a mobile oceangoing platform has many advantages over a fixed location. One is that it makes it possible to move the cable out of the way of major storms and even orbital hazards. Another is that most of the equator runs through the ocean, so that a floating anchoring point offers a much wider range of possible locations than a land-based connection. It enables the lower end of a space elevator to be put in an area with a maximum of fair weather, a minimum risk of lightning strikes and severe storms, and well away from aircraft routes. The equatorial region of the Pacific Ocean appears to be attractive in this respect. Remote locations on the ocean are also easier to protect against unwanted visitors such as terrorists seeking to cut a space elevator cable, although setting up a defended no-go zone around the platform in international waters will require new international treaties (Fig. 6.3).

A floating anchoring point has its disadvantages as well. One obvious problem is that it will move due to currents and waves. A system compensating for this motion by reeling cable in and out and thus avoiding too high tension will be necessary. Another issue may be the exposure to salt water, which is very corrosive and could damage sensitive space elevator equipment such as climbers and reels if not sufficiently protected.

Figure 6.3: Artist's fanciful impression of an ocean-going space elevator anchor station. (Courtesy of the LiftPort Group.)

12,000,000th Floor: Space

The key to the construction and operation of Edwards's space elevator are the mechanical climbers. They will be required to deploy parallel cables and to transport additional countermass to the end of the space elevator, and then to transport people and cargo from Earth to space and back (Fig. 6.4).

In contrast to a launch with a rocket, riding up a space elevator does not require strong accelerations, does not impose violent vibrations, and does not involve a high risk of explosion. That means payloads can be built less robustly, can be launched fully deployed, and can be switched on while still attached to the climber. Testing shortly before detachment from the space elevator can identify problems, in which case the payload can be brought back down to Earth for repairs. A rocket launch allows verification only of the correct functioning of a spacecraft after release and the deployment of solar arrays and antennas, and does not allow a return in case of malfunctioning (except in the case of the Space Shuttle).

Using conventional elevator designs, like those used in apartment buildings and skyscrapers, is not a good idea because the extremely long cables required to haul the elevators up into space would be extremely heavy and difficult to handle (as described before, they may be used to haul up countermass and heavy loads, but for transporting satellites and small amounts of cargo they would be overly complex). It makes more sense to equip the climbers with some kind of mechanism that grabs the space elevator cable and a motor enabling it to pull itself up. A commonly shown design involves two tracks, like on a tank, sandwiching the elevator cable between them. Moving the tracks simultaneously allows the climber to roll up and down the cable. The tracks will need to put a sufficiently high pressure on the cable to prevent the climber from sliding down, but on the other hand not squeeze so much that it damages the tether.

The problem with tracks is that they wear out relatively quickly because they need to be thin enough to be able to bend around the rollers. Also there is a lot of friction involved in track systems, making them much less energy-efficient than wheels for high-speed travel. A more practical design may therefore use wheels instead of tracks. A promising concept is the capstan design, which wedges a cable between a series of wheels (Fig. 6.5).

Another issue is the speed of the elevator climber. The geostationary point, the most likely location for the main center of activity on a space elevator, is 36,000 km (22,000 miles) up. Covering that distance is equivalent to traveling almost once around Earth! A climber moving at 200 km per hour (125 miles per hour) will take over a week to get up to GEO, making it more like a very long train journey than a ride in an elevator.

Figure 6.4: Artist's impression of a space elevator climber/lifter. (Courtesy of the LiftPort Group.)

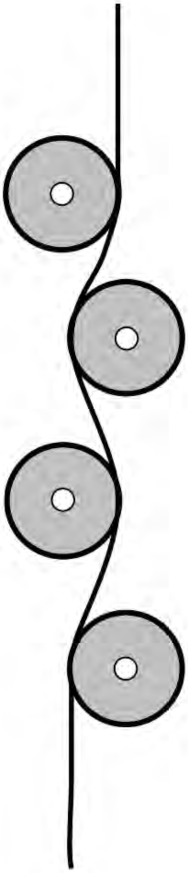


Figure 6.5: A capstan design for grabbing and moving a climber along a space elevator tether.

As the vehicle will be moving through the Van Allen belts at relatively low speed, radiation is a very important issue if people are onboard. The Apollo spacecraft on their way to the Moon moved through the belts at 10 km per second (6 miles per second) and traversed them in half an hour. At 200 km per hour (125 miles per hour), however, a crawler will take about 90 hours to get through the radiation belts. In that long time passengers will accumulate some 100 rads of radiation, with acute radiation sickness as a result (500 rads is sufficient to kill you). Heavy shielding will be necessary for passenger crawlers, for example, with dense materials such as lead, but also thick layers of water in storage tanks surrounding the spacecraft will work. The benefit of using water is that it can afterward be used in the stations on the space elevator, as the water does not get contaminated by acting as a radiation shield (on the other hand, it may be needed again for radiation shielding on the return trip down).

At Earth's surface, the space elevator cable and base station have a horizontal velocity of about 465 meters per second (1530 feet per second), due to the rotation of Earth. Up at the geostationary point, the space elevator has the local orbital velocity of 3.1 km per second (1.9 miles per second). The horizontal speed of each part of the space elevator ribbon thus increases with altitude proportional to the distance from the center of Earth; the further out, the faster it goes. As a payload is lifted up a space elevator, it therefore not only gains altitude but also horizontal speed (or "angular momentum"). The source of this speed is Earth's rotation; according to the physics law that describes the conservation of angular momentum, Earth will slightly slow down as the climber speeds up. However, since the climber's mass is insignificant compared to the mass of our planet, the effect on Earth's rotation is immeasurably minute.

As the climber ascends, it is thus accelerating in a horizontal direction. That means it is constantly moving slightly slower than the point of cable that it moves onto, "dragging" the cable slightly to the west. Depending on the speed of the climbers and the tension the countermass exerts on the cable, this can generate an amount of lean on the lower portion of the cable—on the order of a degree or so for Edwards's space elevator design. This should not be a problem, but too heavy climbers moving up too fast could drag the cable so far out of the vertical that the space elevator could become dangerously unbalanced. Mass and velocity restrictions will thus apply to the climbers allowed to move up the space elevator.

Over the long distances that climbers will travel, reliability can be a problem; wheels with a half-meter (20-inch) diameter will rotate 64 million times getting all the way up a 100,000-km-high (62,000-mile-high) space elevator, and still almost 23 millions times to get to geostationary altitude. Wheeled vehicles moving at high speed normally need some maintenance before reaching 36,000 km on their clock, but repairs on the way up will be difficult. The level of confidence that a climber will make it at least to the nearest maintenance station (likely to be at an altitude of 36,000 km) will thus need to approach 100 percent. Space elevator climbers will thus have to be constructed for durability, using high-quality materials, robust mechanisms, and various backup systems.

Electromagnetically suspended elevators, somewhat similar to the magnetic levitation (maglev) trains already in operation, would not touch the cable at all and therefore enable much higher velocities and experience lower wear and tear. However, such a system would be even more complex than a mechanical climber, mostly due to problems related to running electrical power up a 36,000-km maglev track without enormous line losses (maglev trains are propelled by an electromagnetic system in the guide rail instead of an onboard engine).

But even a mechanical, relatively low-velocity climber system introduces a problem: how to power the climbing mechanism? The amount of total energy required is actually quite low. Where a rocket has to provide both potential energy ("height energy") as well as kinetic energy ("velocity energy"), a space elevator climber effectively gets its orbital velocity from the spinning Earth; it automatically attains the rotational, horizontal velocity of the space elevator as it climbs up. In theory, a climber would thus need sufficient power only to climb up to GEO altitude at a very modest vertical velocity. The decreasing level of gravity on the way up limits the amount of energy required for this even more. Some 50 cents of generated electricity per kilogram climber would theoretically be sufficient. In reality it will cost much more than that, due to energy losses in the climber's electric motors and because of friction between its locomotion mechanism and the space elevator cable. According to Edwards, each 20-metric-ton (44,000-pound) climber will require some 2.4 megawatts of power, roughly the amount of electrical energy needed to run 800 busy family homes.

In addition, energy is lost in the transportation of electricity to the climber over distances of thousands of kilometers. The long distance makes it highly impractical to connect power lines to the climber from Earth or space, or even to use the conducting capabilities of the carbon nanotube space elevator cable itself. (Nevertheless, Yoshio Aoki, a professor of precision machinery engineering at Nihon University and a director of the Japan Space Elevator Association, told *The Times* [London] in September 2008: "We are thinking of using the technology employed in our bullet trains. Carbon nanotubes are good conductors of electricity, so we are thinking of having a second cable to provide power all along the route.")

Equipping the climbers with solar arrays is also no solution, because they would need to be too large and therefore too heavy. At maximum theoretical efficiency, any solar array would be unable to provide enough power to move its own mass from Earth up the elevator, let alone the additional mass of the rest of the climber system. Using the movement of the space elevator tether through Earth's magnetic field to provide electrical power to the climbers (like an electromagnetic drag tether) does not provide enough power either. Nuclear reactors sufficiently light and compact to be installed on a climber do not exist and are not likely to be available anytime in the foreseeable future.

The one practical way of getting power to a climber that space elevator designers currently focus on is beaming energy in the form of laser light from the Earth's surface. The climber receives the incoming light on a photo-voltaic array (similar to a solar array), which converts it into electrical power for the climbing system's electromotor. Laser light packs much more power than sunlight and can be formed into a tight beam that does not disperse much even over very large distances. The equipment required to generate and send out the laser beam would be heavy and bulky, but that would not matter as the laser generator would be located on Earth at the foot of the space elevator.

Powerful laser generators are already under development. An impressive example is the Airborne Laser, intended to shoot down ballistic missiles from onboard a heavily converted Boeing 747 airplane. The system uses a megawatt-class laser, aimed at a target by a large telescope in the nose of the aircraft. A smaller laser measures disturbances in the atmosphere and sends corrective signals to adaptive optics in the telescope, making it possible to accurately focus the megawatt laser onto a pressurized area of a boosting missile. The heat from the concentrated energy will then cause the rocket to break apart. At the time of writing, the full system is to be demonstrated on a real flying missile in 2009. The weapon has an effective range of hundreds of kilometers (the precise specifications are secret), so its technology should be a good start for a space elevator laser energy beaming system.

Space elevator climber technology development is actively supported by the Spaceward Foundation, which has been organizing the Space Elevator Beam Power Challenge every year since 2005. For this competition, participating teams design and build climber prototypes, which then have to race up a vertically suspended tether using only power beamed up to them from the ground. Developing a climber is not an easy task, as the designers have to find the right mix of lightweight structure, efficient motors and traction mechanisms, efficient photo-voltaic arrays, and effective thermal control and other equipment. In addition, they have to provide a sufficiently powerful system for beaming the required energy to the climber. "In broad strokes, the goal of the Space Elevator Games is to bring the Space Elevator closer to reality," the Spaceward Foundation writes on its website. "The goal of the power beaming challenge is to promote power beaming technology. We think that the time is ripe now to move the competition to the next level, addressing real-world power beaming scenarios where the minimum requirements for such systems start at the kilometer range and kilowatt power levels." Apart from furthering space elevator development, the competitions are also intended to inform the public about space elevators and demonstrate to them that it is more than merely science fiction.

The objectives for the 2008 competition are climbing a tether of 1 km (0.6 mile) in height, at a minimum speed of 2 meters per second (6.6 feet per second), carrying as much payload as possible. A high performance prize will be awarded to teams that can move at 5 meters per second (16.5 feet per second) and faster. The climber's net weight is limited to 50 kg (110 pounds). There is no limit set on the amount of power beamed up; the competitors are encouraged to build the most powerful beaming system they can devise. The foundation provides the tether, which is suspended below a balloon that is kept in place by three anchor cables. The rating for each climber is calculated as follows: speed multiplied by the amount of payload, divided by the net weight. For example, a 30-kg climber carrying 10 kg of payload at an average speed of 3 meters per second will have a score of 1 (3 times 10 divided by 30).

The prize money, for the 2008 competition a total of $2 million, is provided by NASA's Centennial Challenges program. NASA has pledged to sponsor the Space Elevator Games from 2005 through 2010 with a total of $4 million. The Spaceward Foundation has been slowly increasing each year's prize money, in line with the growing difficulty level of the challenges. In 2005, for the first competition, only a handful of teams participated in Mountain View, California. Back then the goal was to climb a 50-meter (160-foot) ribbon using a power source, in the form of a searchlight, provided by the organization. None of the climbers went up fast enough, so the NASA-provided prize money stayed in the purse for 2006. For the second edition of the event, the teams had to bring their own power source. Searchlight, laser, microwave, and sunlight concentrating mirror (heliobeaming) systems were put at the bottom of the ribbon, but only five climbers made it all the way up the 50-meter (160-foot) course. The Canadian Team USST from the University of Saskatchewan came within 2 seconds of claiming the prize, but again no money was awarded.

In 2007 a leap in the technology was applied, with two of the 22 teams putting together laser-based systems complete with automated tracking and ground-to-climber data links to scale the 100-meter (330-foot) tether. The overall winner was once again Team USST from the University of Saskatchewan, which managed to move its laser-powered 25-kg (55-pound) climber at an average velocity of 1.8 meters per second (6 feet per second). Moreover, the team did this four times within 40 minutes, demonstrating the reliability of its design. Team Kansas City Space Pirates demonstrated the fastest short climb, moving at over 3.5 meters per second (11.5 feet per second) using only directly reflected sunlight. Unfortunately, its climber was later damaged by a wind gust and never regained its full power. In spite of the impressive successes, in this third event again none of the teams reached the threshold necessary to win the prize money (Fig. 6.6).

The tether in the 2007 event was a 100 meters (330 feet) long, so the 1-km

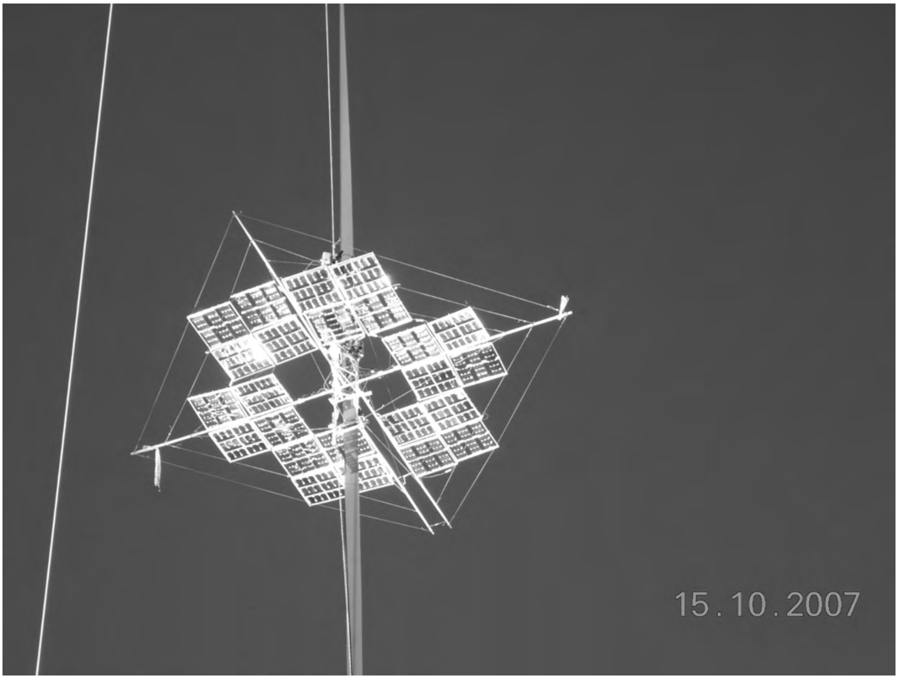


Figure 6.6: The climber of Team Kansas City Space Pirates scales the tether during the 2007 Space Elevator Beam Power Challenge. (Courtesy of Kansas City Space Pirates/The Spaceward Foundation.)

(0.6-mile) tether used for the 2008 event represents a major leap in complexity; not only is the climb much longer, but the beaming of sufficient energy to such a high altitude is much more difficult. To enable teams to participate financially, laser companies sponsoring the 2008 competition will supply the equipment necessary to beam sufficient power to the competing climbers.

In parallel with the Space Elevator Beam Power Challenge, the Spaceward Foundation organizes the Tether Strength Competition. For this, teams have to provide a closed-loop tether of at least 2 meters (7 feet) in length, weighing no more than 2 grams (0.07 ounces). The tethers are put under tension until they break. For the 2008 competition, the foundation awards a total of $1 million of NASA-provided prize money to the teams with the best space elevator tether sample, under the condition that they can beat the best commercially available tether by a factor of two. That means that the 2-gram tethers need to be able to handle a force of over 8000 newton (equivalent to a suspended load of 800 kg [1800 pounds]).

Provided that all the challenges with nanotube materials, power transfer, and climbing mechanisms are solved, what would a ride up a space elevator be like? For a start, it would be completely different from the bone-rattling trip into orbit onboard a conventional rocket. That typically takes 8 minutes from lift-off to low Earth orbit, during which passengers experience acceleration forces of three times their weight or more, followed by an instant, stomach-churning switch to zero gravity. In contrast, climbing a space elevator could take weeks but would be extremely benign on the body (providing there is sufficient protection from radiation). Inside a sufficiently comfortable "wagon," the journey would be spectacular yet elegant, something like a holiday cruise into space rather than the adrenaline kick of a rocket flight.

Going up, for the first 10 km (6 miles) or so, the world beneath would look like what you see out of the window onboard an airliner. However, a couple of kilometers higher, Earth's curvature would become noticeable, such as is seen from the cockpit of a high-altitude fighter jet or spy plane. At an altitude of around 50 km (30 miles), the sky would turn black and, looking away from the Sun, the stars would become visible during daytime. Most of the atmosphere would already be below the climbing vehicle. At 150 km (95 miles), Earth would appear as a partial sphere. At 350 km (220 miles), passengers would feel a bit light on their feet as gravity is a noticeable 10 percent lower than on Earth's surface. The 50 percent gravity level would be crossed at around 2600 km (1600 miles), about 13 hours into the trip if the climber moves at a speed of 200 km per hour (125 miles per hour). Things falling out of the passengers' hand take 40 percent more time to hit the ground than on Earth's surface. At an altitude of 36,000 km (22,000 mile), which would be the geosynchronous orbit stop, passengers would be floating around in microgravity conditions, looking at an Earth the size of a baseball held at arm's length. The lower gravity levels are a result of Earth's gravity decreasing with altitude, and a small contribution of the centrifugal force caused by the rotational velocity on the space elevator (which increases with altitude).

The gradual reduction of gravity experienced while going up a space elevator may reduce the number and severity of "space sickness" cases. Space sickness feels a lot like the motion sickness one may experience on a boat. About two out of three astronauts suffer from it, while one in seven will even experience severe nausea and vomiting. The discomfort usually starts early after arriving in orbit (onboard a rocket), and it normally takes a couple of days for an astronaut to adapt. A person inside a space elevator climber may lose the space sickness symptoms during the journey up, and be fully adapted by the time he reaches zero gravity conditions at the geosynchronous orbit station.

Another interesting possibility offered by the gradual change in gravity is the simulation of gravity levels at other planets and moons. In a station placed about 4000 km (2500 miles) high up the space elevator, passengers would experience Mars gravity conditions, at 38 percent Earth gravity. At an altitude of 9000 km (5600 miles), the gravity level would be that of the Moon—a sixth of that on the Earth's surface. In such stations astronauts could train for interplanetary missions, or recover from long-duration missions spent in low- or zero-gravity conditions. A space elevator would make it possible for them to slowly reacclimatize to Earth's gravity before descending further to the surface.

Out of Order

As we have seen before, low Earth orbit is full of space debris, with close to 10,000 complete satellites and rocket upper stages and some 110,000 pieces of spacecraft larger than 1 cm (0.4 inch) hurtling around our planet at orbital speeds. Without any precautions, the space elevator ribbon could be hit by such a relatively large piece of debris once every couple of hundred days. These collisions could well damage even the space elevator's superstrong fibers. Fortunately, objects larger than 10 cm (4 inches) in diameter are tracked by ground-based radar. With a mobile base on Earth, a space elevator could dodge such large pieces of which the orbits are well known; 10- to 20-km (30- to 60-foot) movements of the anchor point are expected to be needed about every 6 days.

This still leaves a space elevator vulnerable to impact by dangerous pieces of roughly 1 to 10 cm (0.4 to 4 inches) in diameter, which can instantly damage a carbon nanotube ribbon but are too small to be tracked by radar. However, the shape of the ribbon Edwards foresees, which is wide and thin, makes it resilient to small holes. Any holes may be patched over (although it is not yet clear how to do that for nanotube fiber material that has not even been invented yet), or discrete cable segments could be replaced. In the worst case, the entire damaged ribbon could be substituted by deploying a new tether alongside it. Impacts of very small pieces, like flakes of spacecraft paint or naturally occurring micrometeors, will not cause immediate damage but slowly wear out a space elevator ribbon. After a certain amount of time replacement tethers will thus be necessary anyway. The damaged tether may even be reeled back in or brought down by a climber for repair on Earth.

Another impact risk mitigation action is to make the ribbon wider and increase the number of fibers in the zone of low Earth orbits, where the debris is most plentiful. That would increase the chances of a hit, but lower the risk that one could sever the cable entirely. The ribbon can also be curved like a curl or a strand of DNA, so that the chances of an object hitting it edge-on and cutting through its entire width are a great deal reduced. A fully developed space elevator as proposed by Edwards will furthermore incorporate many individual, parallel tethers. This also results in increased robustness, especially if the tethers are separated from each other by some distance (tether design and production are discussed in Chapter 7). Nevertheless, space elevator proponents generally see impact damage mitigation as one of the top critical challenges for the space elevator.

A second highly important threat to the space elevator is the atomic oxygen present in the high atmosphere. Normal oxygen, in its relatively stable form, consists of two oxygen atoms bound to each other. At high altitudes the Sun's radiation is able to break the atomic bond, resulting in single oxygen atoms that are extremely corrosive. They can be found at altitudes roughly between 60 and 800 km (40 and 500 miles), with a peak density at around 100 km (60 miles).

In 1984 NASA's Space Shuttle Challenger deployed a special research satellite, called the Long Duration Exposure Facility (LDEF). Part of its mission was to study the effects of long-term exposure to the space environment of various materials, for which the LDEF was covered with a range of samples. The Space Shuttle Columbia retrieved the spacecraft in 1990 and brought it back to Earth for detailed investigation. It turned out that carbon fiber and epoxy composites on the front of the LDEF, the part colliding head on with the atomic oxygen in the wispy upper atmosphere, were worn down considerably. If future tether materials based on carbon nanotubes and epoxy have a similar vulnerability to the atomic oxygen onslaught, a space elevator ribbon could be wearing down at rates up to 0.12 millimeter (0.0047 inch) in 10 years. That may not sound like much, but a sufficiently strong individual space elevator ribbon may only be a micron (0.001 millimeter, 0.00004 inch) thick and could thus be completely worn through in about a month! The tether would break much earlier, when its residual strength would drop below the minimum level required to handle the forces on the space elevator.

The part of a space elevator ribbon flying through the atomic oxygen layers at the altitude that LDEF orbited will not be moving at orbital velocity, so the wear there should be considerably less. On the other hand, LDEF was not flying at the height with the highest atomic oxygen density, where there are two times more free oxygen atoms per cubic meter. These two considerations happen to cancel each other out, resulting in a worst-case space elevator ribbon erosion similar to what was seen for the carbon/epoxy material on LDEF. Fortunately Edwards and his colleagues have a solution: coating the ribbon at the vulnerable areas with a layer of gold or platinum a few microns thick. The LDEF experiments showed that these materials are unaffected by atomic oxygen and can thus form an effective protection. Making the carbon nanotube fibers a bit thicker in the atomic oxygen zones would also help. The most mass-effective solution will likely be a combination of the two protection measures.

Edwards and his team have also looked at other potential threats to a space elevator, such as rough weather, electromagnetic forces, and radiation. Hurricanes are dangerous, but their impact could be minimized by lowering the ribbon's surface area for the first 8 km (5 miles), using a lower width compensated for by an increase in thickness to maintain the necessary strength. Locating the connection point on a high mountain can also reduce the aerodynamic loads, but severely limits the possible locations for a space elevator base and is not compatible with a mobile anchor station. Transporting construction materials and payloads up a mountain is also much more difficult than shipping them to a floating base station at sea.

Lightning could potentially damage a space elevator, but locating its anchor station in a relatively lightning-free zone such as the equatorial Pacific near Ecuador would help a lot. In such areas lightning storms are rare and very limited in size and extent. The mobile anchor station could move the lower end of the space elevator out of the path of these storms. An additional protection may be coating the ribbon with a nonconducting material.

Electromagnetic forces in the space elevator ribbon (remember the electrodynamic tether principle) will not be strong enough to cause problems like with the shuttle's Tethered Satellite System, which burned through. Because the space elevator rotates with Earth, it does not move relative to our planet's magnetic field, which rotates together with Earth. The space elevator's speed with respect to the magnetic field is thus zero, and no electric currents are induced. The electrical charge of Earth's ionosphere in principle could result in currents running through a space elevator cable to the ground. However, because of the long distance and the relatively low electrical conductivity of the tether, these currents should be mild (the carbon nanotubes in the cable are superconductors, but the epoxy binding them together will not conduct much electricity).

Radiation from Earth's Van Allen belts and the Sun does not affect carbon nanotubes, but could degrade certain epoxy materials. Careful selection of the applied materials should avoid problems in this area. Terrorist attacks are a concern, but locating the anchor station at a remote site in the equatorial Pacific and protection by military forces should minimize the risk that anyone would be able to severely damage a space elevator.

In the case that the elevator cable does break for whatever reason, the uppermost part of the space elevator will drift upward for some distance (the closer to the base the cut occurs, the less the severed part goes up). It may then be possible to attach a mass to it, pulling the space elevator down and enabling reconnection to Earth using a new extension. Another option would be for the center station at GEO altitude to detach itself completely from the cable, cutting its connection to both the remaining segment of damaged tether below as well as the upper part that is connected to the countermass on top. Without any length of cable pulling it up or down, the station would remain in a stable geostationary orbit and could later be reattached to a new space elevator cable.

While the upper part of a broken space elevator goes up, the lower segment will inevitably fall. In many older science-fiction stories the space elevator cable is a massive affair that, when cut, comes crashing down from space and leaves huge scars on Earth's surface. With a carbon nanotube ribbon, however, most of the lower part falling to Earth will burn up in the atmosphere, just like a reentering satellite. The lowest couple of thousand kilometers could survive the fall, but the paper-thin tether ribbons considered by Edwards would have a mass of less than 10 kg/km. They would therefore come down with about the same velocity as a falling sheet of paper, and thus would not cause injury to people. Nevertheless, being super-strong, the ribbons could be difficult to get rid of and could create a nuisance or even result in dangerous situations. It may therefore be better to have broken ribbons fall into the sea rather than on inhabited areas.

What happens if passengers accidentally fall off a space elevator? Not much, if it happens at the geostationary point, because they will be in a circular orbit moving at the same speed as the space elevator. They might slowly drift away, but with a simple rocket system like those already incorporated in modern astronaut space suits they could easily fly back to safety. If they get detached lower down the space elevator, they do fall, but not vertically as is the case in a fall from the roof of a skyscraper. Their horizontal velocity ensures that they would enter an elliptical orbit, with the apogee at the altitude at which they became separated from the cable. The critical issue is then the height of their orbit's perigee. If they fell off below an altitude of 23,000 km (14 miles), they will be in trouble because their orbit will intersect the atmosphere sooner or later, and they will inevitably reenter (i.e., burn up). Falling off between this critical altitude and the geostationary point, they enter a stable elliptical orbit that brings them back to the starting point one revolution (and less than a day) later. It would not do them much good because the elevator would not be there when they get back, but they might be rescued by a spacecraft dispatched from the space elevator.

Detachment at altitudes above the geostationary point means that the passengers are slung into an elliptical orbit, with the perigee located at the altitude at which they fell off but with an apogee that is higher than that, and with a period of 1 day or more. The higher up they disconnect, the higher the apogee. Above an altitude of 47,000 km (29 miles) they move off at a speed that exceeds the local escape velocity, and fly away into interplanetary space.

Instead of accidentally falling off, it is also possible to intentionally release spacecraft. From the previous description it is clear that a variety of equatorial Earth orbits can be entered this way, and Jerome Pearson has shown that all the planets can be reached by launching spacecraft from the tip section of a sufficiently long space elevator.

Step by Step

It makes sense to build technology prototypes and subscale space elevators before attempting to construct a real one. The LiftPort Group has published a roadmap that presents a stepwise approach, where the complexity of the technology and prototypes increases with time. This allows space elevator engineers to gradually build up experience and to solve the problems they encounter before moving on to the next major development (Fig. 6.7).

The LiftPort roadmap starts with two balloon-lofted tethers for testing tether materials, dynamics, and lifter technology (LiftPort calls its climbers “lifters”). A first tether is planned to reach up to an altitude of 3 km (2 miles) and a second to 10 km (6 miles). Both are to be ascended by experimental lifters powered by batteries rather than beamed energy, because the LiftPort roadmap initially focuses on development of the actual lifter rather than the power supply. According to the original plan that was published in 2006, this early development phase was to last until about 2010. LiftPort did put up a 1.6-km (1-mile) balloon tether in January 2006, but the battery-powered lifter managed to get only about 460 meters (1500 feet) above the ground. Even taking into account the achievements of the Space Elevator Games, the current development of the space elevator is thus somewhat behind LiftPort’s schedule. On the other hand, the Games already incorporate climbers/lifters powered by laser energy beamed up from the ground, which is a more advanced stage of lifter power supply technology than that incorporated in the two high-altitude balloon experiments originally planned by LiftPort.

A next step in the plan is the development of a powerful laser system for

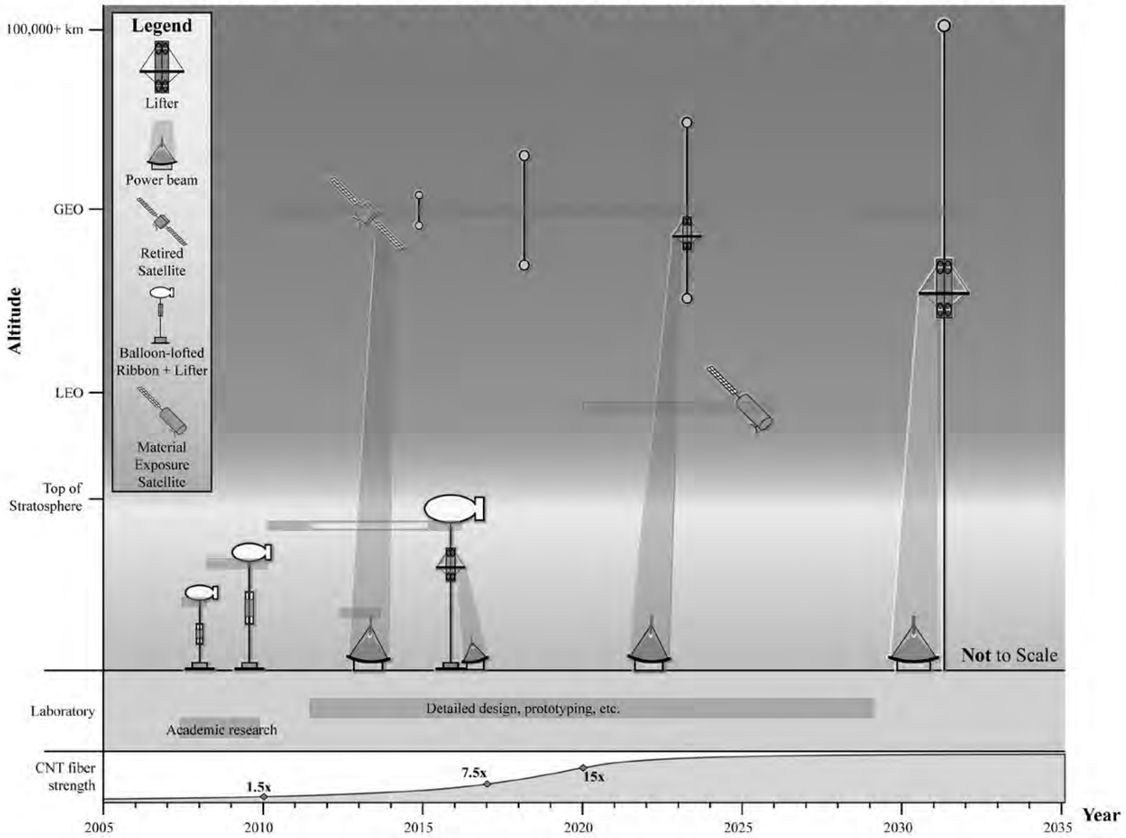


Figure 6.7: The LiftPort Group's space elevator technology development plan. (Courtesy of the LiftPort Group.)

beaming energy to lifters at very high altitudes. A prototype could shine its laser light on the solar arrays of a (retired) satellite, to test target tracking, to test the focusing laser beams from the ground, and to verify how much energy actually reaches through the atmosphere to orbital altitudes. Continuing tether material development should make it possible by 2015 to deploy a stratospheric balloon, reaching 30 km (19 miles) or higher, with a suspended tether strong enough for small lifters to ascend. These lifters could then be powered by a powerful laser beam sent up from the ground.

In parallel to the laser system development, LiftPort suggests the launch of GEO tether-satellites with increasingly longer cables, for the testing of tether deployment and dynamics. Between 2020 and 2025, a satellite could be launched with a tether some 30,000 km (19,000 miles) long, incorporating a lifter powered by the latest ground laser beaming technology. In addition, a material exposure satellite launched around 2020 is intended to test how space elevator ribbon material holds up in low Earth orbit and the atomic oxygen present there. Around 2030 all required technologies should then be sufficiently mature for a full-scale space elevator to be constructed, although this heavily depends on the success of each development step and especially the improvements in carbon nanotube ribbon strength.

Edwards has much criticized the LiftPort plan in a document he posted on www.spaceelevator.com. According to him, tether material development is already well ahead of LiftPort's roadmap, and laser tracking and focusing has already been sufficiently demonstrated by the military. Data on material exposure to the space environment is available from NASA's Long Duration Exposure Facility (LDEF) mission since the early 1990s. Moreover, LiftPort's material exposure satellite would move much faster than a space elevator tether at the same altitude, and therefore not realistically test material degradation due to atomic oxygen. Edwards also states that some critical issues have not been addressed, such as "acquisition of financing, regulatory approvals for deployment and power beaming, ribbon design studies and testing, deployment spacecraft design, ribbon deployment studies, detailed laser and power beaming studies, system protection, system trade-off, system integration, etc."

It is evident that a stepwise approach to the development of something as complicated as a space elevator is required, but exactly what the roadmap should look like is much less clear. Let us hope that whatever development logic will be implemented, it will be more successful than the construction of the mythical Tower of Babel.

Elevators on the Moon and Mars

If space elevators can be deployed around Earth, they could in principle also be used on other planets and moons. Of course it would be more difficult to transport the necessary equipment that far out, but there are also important benefits. The lower a planet's gravity and the faster it rotates, the easier it is to build a space elevator. Theoretically, it will thus be easier to build a space elevator on the Moon than on Earth, as the gravity on its surface is only one sixth of what we feel here on Earth. (On a small asteroid that has barely any gravity, a simple tower built out of conventional materials would suffice, but it would not be a very useful structure.) The forces on the cable are therefore much lower; instead of revolutionary, not-yet-existing carbon nanotubes, a lunar elevator could be made using already-existing tether materials such as Kevlar and Spectra.

Apart from enabling easy access to the Moon's surface, a lunar space elevator could transport into space raw materials mined on the moon. From there it could be transferred to orbiting factories or Earth itself. The lunar regolith contains oxygen that could be used in spacecraft propulsion and life support systems, and lunar helium-3 (extremely rare on Earth) may fuel future nuclear fusion reactors. However, a lunar space elevator would need to be rather different from one based on Earth. While our own planet rotates around its axis every 24 hours, the Moon makes only one turn every 29 days with respect to the Sun. Because this is the same amount of time it takes to complete one orbit around the Earth, we always see the same one side of the Moon. The slow rotational velocity of the Moon compared to Earth means that a longer space elevator is required to generate the same amount of centripetal force in the cable. However, the lower lunar gravity means less centripetal force is necessary to keep the space elevator from falling down, which partly compensates for the slower rotation. If we do the calculations, we find that the Moon's theoretical stationary orbit altitude would be about 88,000 km (55,000 miles) above the surface. However, at such a distance from the Moon, Earth's gravity is certainly apparent and would severely distort the orbit of a satellite or space elevator station put there (the average distance between Earth and the Moon is 384,000 km [239,000 miles]). In other words, there is no equivalent of a geostationary orbit for the Moon. Nevertheless, there are alternative points for positioning the center of mass of a lunar space elevator.

Jerome Pearson, the space elevator pioneer, appears to be the first to have thought up a practical space elevator concept for the Moon. He determined that the center of mass of a lunar space elevator could be placed at either the Moon–Earth L1 or L2 Lagrange point. Lagrange points are special stable points that exist about any two orbiting bodies, such as the Moon and Earth. The gravitational forces of both bodies on a satellite and the centrifugal force caused by its orbit around the Sun are balanced in these points. L1 is a point between Earth and the Moon, 56,000 km (35,000 miles) above the lunar surface. L2 is on the far side of the Moon, 67,000 km (42,000 miles) up (Fig. 6.8). A spacecraft put in a Moon–Earth Lagrange point can thus in principle stay there indefinitely, always keeping the same position with respect to the Moon and Earth. Seen from the lunar surface, the Lagrange points always stays in the same position, making it possible to connect each point with a fixed spot on the lunar surface by a tether—a lunar space elevator.

Pearson's idea for building a lunar space elevator from the L1 or L2 point is similar to what Edwards proposes for a terrestrial version: a spacecraft carrying a huge spool of cable would be launched to L1 or L2, then slowly drift to higher altitude as it deploys a cable down to the lunar surface. Once anchored to the lunar surface, Earth's gravity pulling at the cable and the countermass at the top would ensure it remains taut and aligned toward the L1 point. Solar- or laser-powered climbers could then climb up from the lunar surface to the top of the cable, delivering lunar material there to

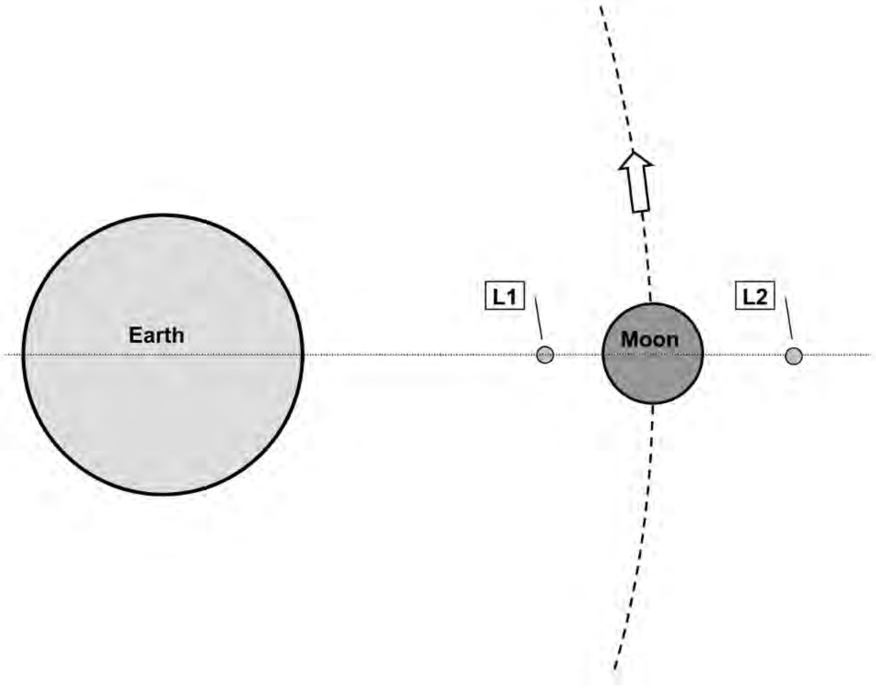


Figure 6.8: Positions of the L1 and L2 Lagrange points of the Earth–Moon system (not drawn to scale).

increase the amount of countermass and thus make it possible for heavier climbers to ascend the cable. Released from the top of the lunar space elevator, payloads would end up in a high Earth orbit and could then be slowed down further (by rocket engines) to enter lower orbits.

According to Pearson, an already-existing fiber material called M5 would be sufficiently strong to build a lunar space elevator. His calculations show that a cable with a lifting capacity of 200 kg (440 pounds) would have a mass of only 6800 kg (15,000 pounds). Once the initial elevator is operational, it could be reinforced with additional materials mined on the Moon, such as glass and boron.

Mars turns once around its axis in 24 hours and 37 minutes, thus spinning only just a bit slower than Earth. At Mars gravity is higher than on the Moon, but still about 62 percent lower than on our planet. The Mars stationary orbit altitude is at about 17,000 km (11,000 miles), thus much lower than for Earth. The net result is that also on Mars a space elevator may be constructed with already-existing materials, and that it can be less than half the height of a space elevator on Earth (at least as far as the distance to its center of mass at stationary orbit altitude is concerned).

Employing an asteroid as a countermass for an Earth space elevator would require somehow capturing such a huge space rock and putting it into Earth orbit above the equator. However, Mars already has two suitable high-mass bodies in near-equatorial orbits: its two small moons Phobos and Deimos. These are actually asteroids, captured by Mars gravity in some distant past. It may be possible to link the surface of the red planet with one of its moons by a long tether. Phobos orbits at an altitude of only about 9400 km (5800 miles)—well below the stationary orbit. To act as a space elevator countermass the orbit altitude of Phobos would have to be significantly increased, because only when the moon is placed above the 17,000-km (11,000-mile) stationary orbit can it exert a pulling force on the cable. However, moving Phobos to a dramatically higher orbit would be extremely difficult and expensive. It makes more sense to employ Deimos as a space elevator countermass, because at an altitude of 23,500 km (14,600 miles) it already orbits well (but not too far) beyond Mars's stationary orbit. Moreover, Deimos contains lots of carbon, which could be used to produce the carbon nanotubes needed for the space elevator ribbon.

Because any type of Mars space elevator will need to extend beyond the nominal orbit of Phobos, and this moon orbits the planet more or less in the orbital plane once every 8 hours, there is a real risk of Phobos smashing through the cable. A solution for this may be to induce a constant oscillation in the cable, sort of a skip rope motion, accurately timed so that the space elevator avoids the moon each time it passes. Arthur C. Clarke described this in his novel *The Fountains of Paradise* in 1979, also suggesting that the high-speed Phobos flybys would offer spectacular views to people on the space elevator.

The Aerovator Alternative

There seems to be only one tether-technology alternative to the space elevator to launch things from Earth's surface into space. Although it has a lot of technology requirements in common with the space elevator, the way it works is quite different.

Imagine a giant taking one end of an extremely long chain in his hand and whirling it around. Then imagine a large part of the other end is shaped like an airplane wing. Just like on a helicopter, that wing will create lift and go up. Now imagine that the chain is so long that the aerodynamic lift elevates the far end all the way up to the edge of the atmosphere. Not only is that end close to space and virtually in vacuum, it is also rotating at a tremendous speed. If an object would be detached from the tip, it would actually fly away at orbital speed and thus become a satellite. If that object would be able to slide along the chain, it would need only a bit of speed starting from the hand of the giant to send it on its way, with the centrifugal force of the rotation speeding it up and moving it to the end of the chain. Now instead of the giant imagine a rotating hub at Earth's surface, and jet engines to propel the system, and instead of the chain imagine a tether ribbon, and you have an "aerovator" (Fig. 6.9).

The aerovator concept was invented and developed during an online Yahoo Group Internet discussion on space elevators in May 2006. The design for this megastructure consists of a tether ribbon with a length of about 1000

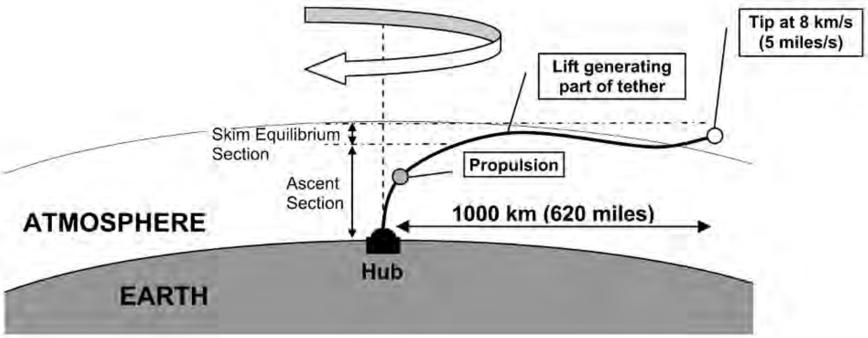


Figure 6.9: Schematic of the aerovator, seen from the side.

km (620 miles) and a total mass of 240 metric tons (529,000 pounds). The aerovator would make one rotation every 13 minutes and needs to be propelled by a 5 mega-newton push provided by jet engines.

The part of the aerovator extending from the ground-based hub into the upper atmosphere is called the ascent section. This section is rotating through the atmosphere, and thus has considerable aerodynamic drag acting on it. The rotational speed increases with the horizontal distance from the hub, and the aerodynamic drag increases with the square of the velocity. At the same time the drag is a linear function of the atmospheric density, which decreases with altitude. This means that the ascent section needs to be kept as short as possible and requires a steep rise; the more vertical this section, the lower the rotational velocity (because of the short horizontal distance) and the less tether length moving through the dense lower atmosphere. However, if possible, the ascent also should be kept shallow enough to allow the payload to slide upward under the influence of centrifugal force alone.

The ascent section needs to contain the propulsion point, where jet engines are envisioned to be attached to keep the aerovator in motion. Existing large jet engines are most efficient at velocities somewhat below the speed of sound (called Mach 1) and at altitudes of around 12 km (8 miles)—the optimal cruise conditions for large commercial aircraft. Calculations on the aerovator show that the optimal location for the propulsion point is between 20 km (12 miles) and 40 km (25 miles) out from the hub in horizontal direction (where the rotational velocity of the tether is between Mach 0.5 and 1). A vertical altitude of 12 km and a horizontal distance of 20 km means an initial ascent angle of 31 degrees. The Internet group calculated that about 20 Boeing 747 jet engines would be required to propel the aerovator and match the aerodynamic drag acting on it. Rather than permanently attaching jet engines, tug planes carrying their own fuel could be docked to the ribbon and relieved by other planes when they are out of fuel or require maintenance.

At 100 to 200 km (60 to 120 miles) out from the hub, the ribbon would extend high enough to enable an equilibrium between aerodynamic lift pushing the tether up and gravity pulling it down, what the group calls a "skim" equilibrium. The skim equilibrium section would also rotate at such extremely high velocities, reaching orbital velocity at the far end of the tether, that the centrifugal force in vertical direction reduces the net weight of the tether and thus limits the amount of lift required (the section is in effect partially in orbit). Preliminary calculations indicate that the low air density offsets the high velocities in such a way that aerodynamic heating should not be a significant problem.

To create sufficient lift, the skim equilibrium section of the ribbon must have an airfoil shape, like the wing of an aircraft. It must also be aerodynamically stable, meaning that it should be able to automatically orient itself to ensure an optimal angle of the wing with respect to the air in the direction of the velocity. This is called a wing's angle of attack. A too shallow angle means insufficient lift, which will result in a drop in altitude, while a too steep angle results in too much drag and eventually a loss of lift due to aerodynamic stall (which happens when the airflow can no longer nicely follow the curvature of the wing). It is likely that aerodynamic stabilizers will be required, as on an airplane. For that, the designers envision very lightweight feathered rods that extend downwind and are attached to the ribbon at a proper angle. The strong tension along the ribbon will ensure that it remains taut, providing lengthwise stability.

Seen from above, the aerovator will have a distinct "L" shape, with the shorter leg being the part of the tether ribbon between the hub and the propulsion point, and the longer leg the part from there to the tip. The shape of the ribbon's path is determined by a balance between centrifugal forces, aerodynamic drag, propulsion, and the tension in the tether ribbon. The section between the hub and the propulsion point is essentially a straight line, with only limited bending due to drag. The pull of the jet engines at the propulsion point creates a sharp, nearly 90-degree bend back with respect to the direction of rotation. From there, the ribbon follows a smooth bend all the way to the tip (Fig. 6.10).

There are two ways to launch a payload with an aerovator. In both cases, the payload starts at the hub and then moves to the tip, where it detaches at orbital velocity. The first method is to use a vehicle that "grabs" the tether ribbon, using a wheel and brake assembly similar to that of a space elevator climber, and moves outward at a controlled speed. At the tip it will have the same speed as the ribbon, that is, 8 km per second (5 miles per second). As this is the local orbital velocity, the payload can then be detached to continue

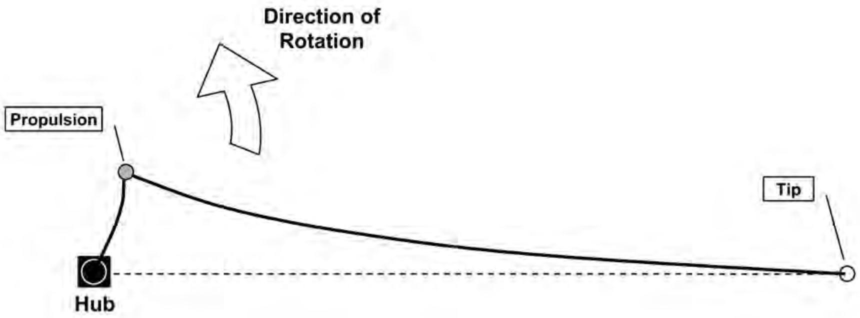


Figure 6.10: The aerovator seen from above.

as a free-flying satellite. Once the payload is released, it can reach its final orbit with the help of a small rocket propulsion module.

The second possibility is to have the payload move freely along the ribbon. Due to the centrifugal force, the payload will automatically accelerate outward, achieving a velocity of about 11 km per second (7 miles per second) when it reaches the ribbon's end (which means it will actually move faster than the tip and thus has more than the minimal orbital velocity when it leaves the aerovator). You can easily demonstrate this principle yourself by twirling a rope over your head and then attaching a free-sliding ring near your hand; it will automatically glide along the rope and be launched away from the tip. A free-moving payload does not require brakes, but a high-velocity, low-friction method of attachment to the ribbon will be needed. Otherwise the tether would quickly wear out, temperatures caused by friction could easily become too high, and the required payload velocity may not be reached. The use of magnetic forces or some form of gas cushioning may be possible.

As the aerovator requires an initial steep ascent, the payload may need some help to get going during the very first part of its trip, where the centrifugal force may be insufficient to overcome gravity. For the "grabbing" payload a powered wheel vehicle could be used; for the free-moving payload this is also a possibility, as it could be released at the point where the centrifugal force is sufficient to carry it along further.

The design group thinks that the aerovator could be deployed entirely from Earth's surface, with the ribbon being played out from the rotating hub and aerodynamically lifting itself up as it is extended. However, as the group points out, the hub will very probably need to rotate much faster than in the fully extended state to make this possible. Using tug-planes for propulsion, the aerovator tether is envisioned to be not much more than a thin ribbon that could be regularly dropped for repairs and redeployed or replaced when needed. Being just a thin and light ribbon, the danger of the aerovator causing serious damage and injuries in case of malfunction is also expected to be very low. If the ribbon were to be cut anywhere along its length, the lowest parts would gently flutter to the ground, while the high-speed upper parts would burn up when falling into the increasingly denser atmosphere. Crewed payload vehicles would need to be equipped with heat shields and parachutes to allow a safe landing in case of a break in the ribbon or a premature detachment, but as these components would be needed anyway to get back to Earth at the end of the mission, that should not be a problem.

Like the space elevator, the aerovator concept relies mostly on the availability of super-strong, lightweight, nanotube materials that do not yet exist. Apart from that, the dynamics of deployment and stability control will likely be very complicated. Nevertheless, although not as far developed as the space elevator concept, the concept seems to be credible.

Space Elevator Versus the Aerovator

The aerovator concept has both advantages and disadvantages in comparison to the space elevator. An important advantage is that the aerovator does not require a countermass in space. Moreover, the aerovator ribbon length would be on the order of a 1000 km (620 miles), while the space elevator needs to be at least 60 times longer (and maybe much more, depending on the type of countermass used). The space elevator needs to be deployed from space, and thus requires that nearly all equipment involved be launched into space ahead of time, while the aerovator can be reeled out from Earth. Also, the space elevator needs to be carefully positioned over the equator, while the aerovator's hub in principle can be located anywhere.

The space elevator reaches far beyond the atmosphere and therefore runs the risk of being hit and damaged by satellites, space debris, and micrometeoroids. Conversely, it also presents a risk for active spacecraft whose orbits it intersects. Although the aerovator covers a greater area than the space elevator, because it rotates in a 2000-km-diameter (1200-mile-diameter) circle, it reaches only to the edge of the atmosphere. There are no satellites there, and the risk of being hit by debris and meteors is relatively low due to the aerodynamic drag that quickly removes them from the area.

Payloads being transported up a space elevator will take several days or longer to reach low Earth orbit and higher, while a payload freely moving along the aerovator can reach its tip in less than an hour, and thus reach any orbit in a couple of hours at most. The shorter travel time may also be more suited to the launch of crewed spacecraft. On the other hand, payloads being launched by the aerovator will be exposed to acceleration levels of up to 5*g* (the rotational acceleration felt at the aerovator's tip), while on the space elevator this can be kept to a steady 1*g*, equivalent to the payload's weight on Earth.

Payloads climbing up the space elevator need a drive train, probably with power being transmitted by powerful laser beams. On the aerovator, payloads are propelled by centrifugal force and may only need some active propulsion and power close to the hub, where the slope may be too steep to overcome by centrifugal force alone. However, because of this centrifugal force, it is very difficult to bring down anything from far up the aerovator back to Earth. For the space elevator this is a relatively simple procedure that requires only brakes.

Moreover, the Internet group that invented the aerovator calculated that the tensile strength of the aerovator tether material would need to be on the order of 5 to 10 gigapascal, meaning that each square centimeter of ribbon cross section should be able to withstand a pulling force of 500,000 to 1,000,000 newtons. The lower limit of this range is equivalent to hanging a weight of 50,000 kg on a wire with a diameter of just over half a centimeter (110,000 pounds on a 0.22-inch wire), or more than 50 cars on a shoestring. This is quite something, but the space elevator tether material would need a tensile strength no less than an order of magnitude higher, something like putting 1000 cars on the shoestring. No tether materials with these kinds of tensile strengths yet exist, but it would be somewhat less difficult to reach the required material properties for the aerovator than for the space elevator.

Concerning the types of orbits that can be reached, there is no clear winner. The space elevator goes up all the way to GEO (36,000 km or 22,000 miles), and payloads released there have exactly the right orbital velocity for that altitude, and so do not need a velocity boost. Payloads detached at 47,000 km (29,000 miles) will have enough speed to escape Earth's gravity and move into interplanetary orbits. However, satellites detached from below GEO altitudes will move too slowly to stay in a circular orbit, and need a rocket stage that gives them several additional kilometers per second of velocity. For very low orbits the main benefit of a launch from the space elevator is the release above the atmosphere, because in terms of velocity the gain is very limited (only 0.5 km/s on the 7.8 km/s required, or 0.3 mile/s on 4.8 miles/s). The aerovator can launch satellites directly into low orbits, but to reach GEO the payloads need several kilometers per second of additional velocity; 1 to 2 km per second (0.5 to 1.5 miles per second) in the case of a free-moving payload release or about 4 km per second (2.5 miles per second) in the case of a "grabbing" payload (distributed over two propulsion boosts—a first one to reach GEO altitude, then a second to attain a circular orbit).

A clear disadvantage of the aerovator is that it needs the equivalent of five Boeing 747 airplanes (each with four engines) to constantly pull it along, while the space elevator will need no more than maybe some short-duration propulsion to move out of the way of chunks of orbital space debris. Another disadvantage is that the aerovator will require the mastering of very complex dynamics, including hypersonic aerodynamics, and thus is much harder to capture in mathematical computer models than the stable, bridge-like space elevator.

All in all, it appears that the aerovator will be less expensive to build than the space elevator, but will cost more to operate due to the fleet of tug planes it requires. The designers think that the aerovator will be more economical because it should be able to launch more cargo in a specific time frame, and travel time to orbit is shorter. However, at present, in the very early conceptual design phases of the space elevator and the aerovator, it is extremely difficult to predict the size of the market, developmental costs, and launch costs. It is possible that there would even be a market for both the aerovator and the space elevator.

Challenges

7

Tethers and space elevators have a wide range of potential advantages over conventional space propulsion and launch technology, which may make space travel more efficient, easier, and cheaper. Then again, the use of tethers in space also faces many challenges. A large number of these can surely be overcome through sufficient amounts of analysis, testing, and money, but others may turn out to present serious hindrances (and to find out if they do may also take a lot of analysis, testing, and money). Too much risk avoidance will not get us anywhere, but being overambitious and wanting too much too fast may be costly and may hamper the continuation of tether technology development (as happened with the two Tethered Satellite System flights of the Space Shuttle, which are generally and somewhat unfairly regarded as unsuccessful, and have not been followed up by any similar mission). This chapter describes some of the most critical challenges to space tether development.

Cable Material

The major challenge for both the space elevator and the aerovator concepts is that the incredibly strong yet lightweight tether material that they require does not yet exist. We have already seen that for his space elevator, Bradley Edwards needs cable material with a tensile strength of 130 gigapascals (1,300,000 kilograms per square centimeter, or 18,500,000 pounds per square inch). An aerovator could be built with a lower strength material, but it still requires a tensile strength on the order of 5 to 10 gigapascals (50,000 to 100,000 kilograms per square centimeter, or 710,000 to 1,400,000 pounds per square inch).

The best fiber materials currently available for tether applications are very strong; Spectra-2000, for example, has a tensile strength of some 4 gigapascals, which in combination with its low mass is sufficient for even rather large-scale tether systems such as the Hypersonic Airplane Space

M. van Pelt, *Space Tethers and Space Elevators*, DOI: 10.1007/978-0-387-76556-3_7,

Tether Orbital Launch System (HASTOL) and the Lunavator. Its performance is also not that far off from what is required for an aerovator, but a space elevator needs a material whose tensile strength is more than 30 times greater. The nonexistence of this "unobtainium" is the main reason why many regard the space elevator as nothing more than an interesting thought experiment, a basis for entertaining science-fiction stories but not something that could become reality in the near future.

In 1991, however, Sumio Iijima of the Meijo University in Japan discovered a completely new material with fantastic properties. He electrically charged superhot carbon soot and put it under a microscope to create and study so-called "buckyballs." These are closed, spherical molecules of carbon atoms linked together in a kind of soccer ball pattern. This atomic arrangement gives the buckyballs an amazing strength, comparable to that of diamond crystals (which consist of tetrahedral box patterns of carbon atoms). To his surprise, he also found various cylindrical, thin-walled structures of chained carbon atoms in the condensed soot he studied—molecules we now know as "carbon nanotubes." The tubes he saw were tiny, less than two nanometers wide (approximately 1/50,000th the width of a human hair), and of various lengths. The individual nanotubes turned out to be lightweight, as stiff as diamonds, and yet a hundred times stronger than steel at one-sixth the weight, and even ten times stronger than Kevlar. Moreover, in contrast to the round buckyballs, the long nanotubes can be woven together into super-strong yet flexible fibers of any required length—just what is needed for a space elevator! It seemed that the "continuous pseudo-one-dimensional diamond crystal" used in the fictional space elevator cable Arthur C. Clarke described in his 1979 novel *The Fountains of Paradise* had been found!

Although Sumio Iijima's discovery made carbon nanotubes known all over the world and initiated extensive follow-up research, it turns out they had been mentioned in several earlier scientific studies. Their history goes all the way back to 1952, when Russian researchers Radushkevich and Lukyanovich published images of 50-nanometer-diameter carbon nanotubes in the *Soviet Journal of Physical Chemistry*.

Unfortunately, it turns out to be very difficult to make long carbon nanotubes; no more than a couple of centimeters in length is all that has been achieved so far. To make such short single nanotubes useful, they need to be spun together into a fiber, like making rope from short shoots of hemp. Progress in carbon nanotube fiber technology has been increasing in pace over the last years. Researchers at China's Tshingua University and the University of Texas in the United States have developed various methods of spinning long fibers out of short carbon nanotubes. At the Second

International Conference on the Space Elevator in September 2003, the University of Kentucky's Advanced Carbon Materials Center announced that it had managed to produce a nanotube-fiber tether just over 5 kilometers (3 miles) long. More recently, a research team at Rice University found a way to align carbon nanotubes in the same direction by combining them with sulfuric acid. This is an important achievement, because individual nanotubes handle pulling forces best if applied in the length direction. As a result, a ribbon in which all nanotubes are embedded lengthwise has the maximum achievable tensile strength; the less they are aligned, the less individual nanotubes help in forming a strong fiber and hence the lower the tension that the ribbon can handle.

Researchers at the University of Cambridge in the United Kingdom are now able to create and spin nanotubes into fibers in a single process, enabling them to produce kilometers of fiber per day. Their method starts with a hydrocarbon base material, such as ethanol, hexane, methane, or diesel. Together with a small amount of iron-based catalyst, called ferrocene, this is injected into a 1300C (2400F) furnace. Due to the extreme heat, the hydrocarbon is broken down into hydrogen and carbon. Using particles of the iron catalyst as a scaffolding, the carbon atoms then merge into cylindrical structures, forming a dark mass of millions of individual nanotubes. To wind it up, a rod is inserted into the furnace to grab the material and pull it out, stretching the entangled mess into a fine thread of lengthwise-aligned nanotubes like wool on a spinning wheel. Further alignment of the nanotubes is encouraged by swathing them in a faint mist of acetone when they emerge from the furnace. The fiber is then spooled on a motorized wheel.

Advances such as these are promising, but for sufficient strength a space elevator ribbon will need to incorporate many such individual threads. This can be done by embedding multiple threads in a matrix, typically a polymer plastic, to produce a composite material tether. The stresses in a space elevator ribbon will require it to consist of about 50 percent nanotube fiber, which is difficult to achieve; practical tether ribbons developed up to now include only a couple of percent of nanotubes. With more of them embedded, the bonding between the nanotubes and the matrix weakens, and the strength of the tether decreases. Improvements in nanotubematrix bonding are necessary to be able to increase the number of nanotubes that can be embedded.

Research on carbon nanotubes and the manufacturing of fiber and multiple-fiber composites is ongoing in many laboratories—not primarily for use in a space elevator but mostly because of potential applications such as super-strong bulletproof vests, lighter yet tougher aircraft structures, bomb-proof refuse bins, and more robust jet engine fan blades. The various ongoing nanotube developments may make a space elevator ribbon with sufficient strength and low mass possible in the not-so-distant future.

On the other hand, any structure as large as a space elevator is likely to have many tiny defects in the construction material, which will lower the overall tether strength compared to that of perfect individual carbon nanotubes. Calculations by Nicola Pugno of the Polytechnic of Turin in Italy, reported in 2006, indicate that inevitable defects in manufactured nanotubes will lead to significant strength reductions. Laboratory tests have shown that flawless individual nanotubes can withstand about 100 gigapascals of tension, but he points out that if just one carbon atom is missing in a nanotube, it can reduce its strength by as much as 30 percent. Ribbon tethers made of many nanotubes, in effect increasing the number and seriousness of defects, are bound to be even weaker, averaging less than 1 gigapascal in tensile strength, according to Pugno. However, space elevator enthusiasts have pointed out that in his calculations he did not include the friction forces between long, closely packed nanotubes. These could make up for defects in individual nanotubes, creating an overall sufficiently strong ribbon. Moreover, nanotubes with buckyball hemisphere structures attached on their sides increase this friction, and can already be produced. Such molecular appendages make it possible to hook nanotubes to each other or to the composite matrix, so that loads can be transferred between individual nanotubes more efficiently. This should result in a ribbon that is much stronger than one that incorporates only smooth nanotube molecules.

Thus, the jury is still out on whether the space elevator based on carbon nanotube ribbons will ever be feasible. It is impossible to predict when the continuous improvements in nanotube ribbon development will run out of steam, and whether that would be well before or after space elevator-enabling ribbons can be produced. Many space elevator enthusiasts are optimistic and foresee a fully operational space elevator rising into space within 30 years or so. Others think that the ribbon material requirements cannot be fulfilled, at least not with carbon nanotube fibers, and that the space elevator will remain a dream for the rest of this century.

Tether Stability and Control

The early tether experiments performed during the Gemini flights gave a first indication of how difficult it can be to deploy a tether in space, which has been further confirmed by more recent test flights. Tethers can get twisted and blocked inside their dispensers or go slack, only to give powerful jerks on the spacecraft when suddenly put under tension. But even after successful deployment tethers can move in seemingly mysterious ways.

All the different ways in which a space tether can oscillate can be easily simulated using a ball hanging on a length of elastic cord. You can bounce the ball up and down, compressing and stretching the cord. This type of movement is called longitudinal oscillation or spring-mass oscillation. You can also induce a circular, skip-rope motion in the cord, or swing it back and forth in a pendulous motion. Quickly moving the end of the cord up and down in a whipping motion develops transverse oscillations, also known as traveling waves. And with some tension on the cord you can make it vibrate like a huge guitar string. Finally, there is torsion, which is rotation along the length axis of the cord. You can simulate this by winding up the cord and letting go. The ball will rapidly spin up, overshoot the zero-stress point, slow down, and then spin up in the opposite direction and so on until the movement dampens out.

Any tether has a number of so-called resonance frequencies at which it “likes” to oscillate in one way or the other. These frequencies depend on the length of the tether, its elasticity, and the tension that is put on it. If the frequency at which a tether is moved due to an external force (like the movement of your hand on the elastic cord of the example) corresponds to one of its resonance frequencies, the movement of the cable can quickly grow in strength. It’s a bit like with a basketball, which you can bounce higher and higher off the ground if you find the right rhythm. If disturbing forces on a tether excite it in just the right way, the induced motion may become so violent that it can break the tether. Even if that does not happen, a viciously shaking tether can damage the spacecraft to which it is attached, or make it lose its attitude control.

An example of what such “mechanical resonance” can do is the famous case of the Tacoma Narrows Bridge in the state of Washington, which in 1940 collapsed in only a mild wind that happened to come from just the wrong direction. The destruction of the bridge was recorded on film by Barney Elliott, owner of a local camera shop (you can easily find this movie on the Internet). His footage shows how the steady wind makes the bridge sway side to side; when the left side of the roadway went down, the right side would rise, and vice versa, with the centerline of the road remaining still. The bridge is twisted ever more wildly, until it eventually collapses. The movie is often shown to engineering, architecture and physics students as a cautionary tale. The collapse of the bridge was due to a steady force, the wind, and the bridge acting as a kind of wing. Part of it would lift up due to the wind, then stall and fall back. The periodic movement was exactly matching one of the resonance frequencies of the bridge, so that the movement could grow in magnitude and force until the structure could no longer cope. There is no wind in space, but the bottom part of a space elevator ribbon may very well be susceptible to just this type of wind-induced torsional vibration.

To complicate things even further, different types of oscillation may interact with each other if the frequency of one movement closely matches the resonance frequency of another type of movement. For instance, transverse oscillations in a tether may cause the attached deployer satellite to swing back and forth like a pendulum. A potential cause of problems in a space elevator is the climbing vehicles going up and down. They could cause transverse oscillations like those in the example of the elastic cord and ball. Jerome Pearson was the first to study the dynamics of this behavior in a space elevator, and found that there will be certain speeds at which climbers should not be allowed to travel up or down the ribbon. However, unlike with conventional speed limits, going slower or faster than a critical velocity would be okay; it is only the small set of discrete speeds that need to be avoided. Moving at wave-inducing speed for a relatively short time—a few hours—would not be a problem either, so the impact of the fixed speed limits would be small.

Electrodynamic propulsion tether spacecraft may experience resonance problems due to the variations in electric power levels when orbiting from the day side to the night side of Earth and vice versa. The resulting periodic changes in propulsion force could cause the tether to swing out of control, depending on its length, mass, and material. Rotating electrodynamic tethers have even more chance of getting into resonance trouble, because as the tether rotates through the magnetic field, the direction of the Lorentz force with respect to the rotation direction changes every half rotation, constantly accelerating and then decelerating the tether. On top of this, the Lorentz force is also higher when the tether rotates in the direction of the orbital velocity than when it rotates in the opposite direction (in the first case the total speed is the orbital plus rotational velocity; in the other case the speed is the orbital minus the rotational velocity). Such periodic changes in the electrodynamic force on the tether can definitely lead to problematic resonance vibrations.

The testing of the deployment and dynamics of tethers tens of kilometers long under microgravity conditions is impossible on Earth. Fortunately, the behavior of tethers can be simulated and predicted with sophisticated computer programs, so that problems can be avoided to a certain extent. For the Young Engineers' Satellite (YES-2) mission (see Satellite Experiments in Chapter 4), a test rig was built that incorporated a deployer system plus a spooling motor to pull on the tether. The motor simulated the gravity gradient forces that in space would pull the tether out of its storage canister; its speed was governed by a computer simulating the deployment velocity that would occur on the real mission. The tension in the tether was continuously monitored, and subsequently used as input for tether dynamics simulations. With this test equipment, the deployment of the 31.7-km-long (19.7-mile-long) space tether could be accurately and inexpensively tested and optimized inside a small laboratory on Earth.

To ensure sufficient control, future large-scale tethers will need to be "smart," incorporating sensors, actuators, and control electronics that continuously check what is happening to the tether and correct unwanted movements. The Lorentz forces on electrodynamic tethers can then be actively controlled, by establishing and breaking the electrical circuit at the right moments, so that dangerous oscillation modes are avoided. Dampeners built into a tether or at the anchoring point of a space elevator can also help to avoid vibrations going out of control.

Damage Protection

The protection of a space elevator ribbon against damage caused by micrometeorites and man-made space debris was described earlier (see Out of Order in Chapter 6), but also other types of tethers will be susceptible to such impacts.

As shown by the Small Expendable Deployer System (SEDS-2) experience, the 19.7-km-long (12.2-mile-long) tether that was severed after only 3.7 days in orbit, the chance of a tether being cut by space debris or a micrometeorite is a major mission risk. Joseph Carroll and John Oldson of Tether Applications have used micrometeorite and debris impact data from the Long Duration Exposure Facility (LDEF) satellite to model the risk of such impacts in low Earth orbit. Obviously, the thinner and longer the tether, the less time it will survive. The time it will take for a tether to be cut is a function of the tether diameter in millimeters plus 0.3, to the third power. The result is in kilometer-years. For example, a tether with a diameter of 1 millimeter (0.04 inch) will be severed within $(1 + 0.3)^3 = 2.2$ kilometer-years. That means that if the 1-millimeter-diameter tether has a length of 2.2 km (1.4 miles), it will likely survive only 1 year in space (and if it would be 1 km long, it would probably survive about 2.2 years).

To limit the risk of debris and meteoroids severing a tether (increasing its kilometer-year survival index), its diameter can be increased. However, this quickly leads to thick and heavy cables. A better idea is to construct a tether out of multiple strands. A simple example of this is a caduceus tether as used in the YES mission, which consists of two or more intertwined strands. Such a tether can be designed so that if one line gets cut, the remaining lines are still strong enough to handle the loads.

A more complex but also more robust option is the so-called Hoytether, developed in 1991 by Robert Hoyt of Tethers Unlimited. This tube-shaped tether is composed of multiple primary strands that are interlinked by diagonal secondary lines, making the tether look like a fishing net. Support rings ensure a cylindrical spacing between the primary lines. In the normal, undamaged situation the secondary lines are slightly slack and do not carry any loads. However, when a primary line is cut, these secondary lines divert the tension around the damaged area. A cut in one or more strands is thus effectively bridged by the interconnections. Unlike for simpler multistrand tethers, where a cut line is completely lost, in a Hoytether a severed line still helps to carry the load in most of the tether; only at the location of the cut do the other primary strands have to compensate for the damage with the help of the local secondary lines (Fig. 7.1).

Hoytethers could be made by hand with the primary and secondary lines connected with knots. However, knotted connections severely limit the strength of the strands, so it would be better to use some other kind of interconnection technique. Moreover, as the tethers would need to be tens of kilometers long, it would not be economical to make them by hand. Fast and inexpensive, knotless mechanical methods are thus required for their practical fabrication.

If a piece of rubber band is stretched and then cut, the pieces snap back violently. This may also happen when a thread in a multiple-strand tether breaks, causing additional damage to the rest of the tether. Freeman Dyson pointed out that the elastic energy stored in a stretched carbon nanotube is so high that a snapping strand could cut neighboring tether strands as well, annihilating the entire ribbon through a cascade of snapping strands. Dyson stated, “If it tears in one place, it is likely to be a disaster.” However, it turns out that carbon nanotubes are very good thermal conductors, so the elastic energy in a snapping strand may quickly dissipate in the form of heat, leaving insufficient mechanical “snap” energy to do serious further damage. Moreover, the mass of a piece of snapping strand of carbon nanotube is rather small, so even if all the elastic energy would be converted into kinetic energy and thus speed, it would probably do little damage; the strand would hit the rest of the space elevator ribbon at high speed but with little power due to its low mass. All these assumptions and considerations need to be verified in a laboratory, so that a space elevator ribbon may be constructed in such a way that breaking strands would not damage other lines (for

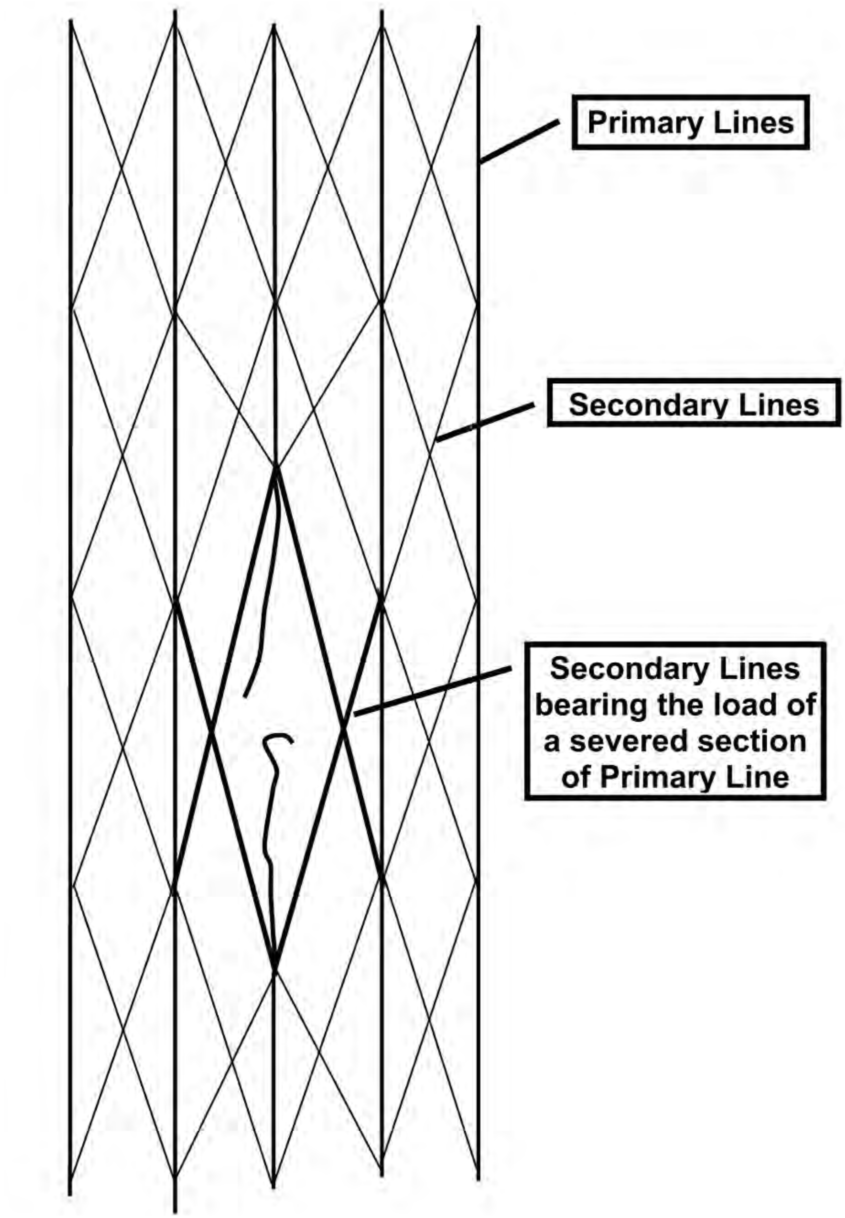


Figure 7.1: In a Hoytether, secondary lines can take the load off a damaged primary line.

example, by reducing the stress on the ribbon or building in sufficient separation spaces between the strands).

The Price Tag

The more ambitious and innovative a space tether application, the more money will be needed for the development but also the more difficult it will be to estimate the cost and predict the benefits. The benefits, in the form of lower launch costs, enhanced capabilities, or increased efficiency, must outweigh the investments in terms of time and money. If benefits from a new development can be expected soon and the financial return on investment is high, technology development may be paid for by private industries. However, for space projects it is typical that new developments need to be at least partly financed by government space organizations, because for industry the financial benefits are often too far in the future and too uncertain.

In Europe the development of the Ariane series of launchers has always been financed by European governments through the European Space Agency (ESA). Only after a successful qualification launch does the commercial operator Arianespace take over, and even then it does not need to pay back the development costs. Developing the original version of the Ariane 5 has cost about $8 billion (in 1996 dollars) and took over 10 years. The revenues obtained from selling Ariane launches are not sufficient to run the operation on a commercial basis and also pay back the initial investments. Because Europe wants to have independent access to space and up-to-date rocket technology, ESA's member states find it worthwhile to finance launcher developments. This is not a typical European situation. In other countries the development of launchers and innovative satellite technology is usually funded by government space agencies or defense organizations (for example, in the United States launcher development is strongly supported by the U.S. Air Force). Scientific space missions are always financed by government space agencies or other nonprofit organizations, because no money can be made on those.

Relatively small space tether projects require modest amounts of money; the financial risks are generally low and development durations relatively short. Projects such as the Small Expendable Deployer System (SEDS) series can be funded as experimental precursor missions, often even by universities. Applications such as the Terminator Tether, for de-orbiting obsolete satellites, may find commercial investors, if the market looks good and the investments and risks are reasonable. However, huge projects such as lunavators and space elevators will cost billions of dollars and take tens of years of development. Moreover, they are technologically and financially risky due to the large numbers of unknowns involved: Do we really understand carbon nanotube ribbon dynamics? What size will the satellite launch market for a space elevator be by the time it becomes operational? How much will it cost to operate and maintain a lunavator? The answers to such questions may require costly research and test programs, or may even not be available before the actual system is put into operation.

Two types of cost are important here: the development cost and the operations cost. The development involves such activities as basic research, test model construction, equipment development, and operations logic development—basically everything needed to make the system operational. The operations cost are those that need to be paid to keep an existing system functioning: maintenance, upgrades, electricity bills, marketing, security services, and so on. Development costs occur only once, while the operations costs recur during the entire lifetime of a system.

Edwards has made some first cost estimates for his space elevator concept. Initially he came up with a total estimate of $40 billion: $20 billion for the "best estimate" plus a 100 percent contingency. In a paper presented in Vancouver in 2004, he and co-author David Raitt were considerably more optimistic. Based on current launch prices, they estimate that it will cost about $1 billion to put the first deployer satellite in space (assembled from individually launched smaller parts). The development of this satellite would cost about $500 million, although this seems to be rather optimistic considering that large, single-launch satellites usually cost well over $1 billion. The production of the not-yet-existing carbon nanotube ribbon is very difficult to estimate at the moment, but Edwards and Raitt's estimate is a total of $390 million for the first space elevator. This number assumes that by the time the construction of the space elevator starts, carbon nanotube fiber production for other applications would already be well established and therefore relatively cheap. Other cost estimates are $370 million for developing and producing the 230 climbers needed to enlarge the space elevator (assuming they are sent up only once, ending their life as part of the countermass), $120 million for an oil rig type of seagoing anchor platform, $1.5 billion for three ocean-going laser power platforms with two lasers each, and $500 million for a space debris tracking radar network. With some $400 million for miscellaneous items and a 30 percent margin on top for risks and unknowns, the total development cost for the first operational space elevator would then be something on the order of $6.2 billion (in 2008 economic conditions).

This is a lot of money, but compared to other large space access investments it is not outrageous. The budget required according to Edwards is even less than the development cost for the first version of the Ariane 5 launcher, while a working space elevator would be incomparably more efficient in launching spacecraft than any conventional rocket. According to

Edwards's estimates, a space elevator would cost even less than the development of large airliners (such as the Boeing 787 Dreamliner, which cost some $10 billion).

It may be better to compare the space elevator's role with large transport infrastructures such as bridges and tunnels. Its development cost is in line with those as well; the almost 4-km-long (2.5-mile-long) Akashi bridge in Japan has cost about $4 billion. The English Channel tunnel linking England with France has cost approximately $13 billion. Even if Edwards's latest estimates for the development of a space elevator are optimistic and the real cost will be considerably higher, the required investments are not prohibitive (assuming that sufficiently strong carbon nanotube tethers can be developed and that there are not other technical difficulties). This means that, at least economically, the space elevator is a much more realistic concept than large space colonies, interstellar spacecraft, and similar grand ideas regularly featured in science fiction.

At the 2008 space elevator conference, Edwards announced an innovative way to fund further space elevator research: he is investigating the feasibility of a combined entertainment and research center, to be called Space Orlando. The entertainment area would involve a 10-story space elevator simulator. Visitors would enter the structure as if they were walking into a real space elevator base station, and then board a climber vehicle for a virtual-reality ascent into space. At the end of the ride up, they would step out into a massive room lined with plasma screens displaying what it would look like to be on a geosynchronous orbit (GEO) space elevator station. Combined with the entertainment facility would be a research center, funded by the tickets sold to Space Orlando visitors, who would also be able to see the research going on at the center. Edwards estimates the facility would cost some $500 million to $1 billion to build and would attract 8 million visitors a year.

In terms of operations cost, to make the space elevator an interesting investment it must provide a way to reduce overall launch costs. Based on the amount and price of the energy needed to bring something up with a space elevator climber and Edwards's estimates of the operations costs of a space elevator, the cost for putting a kilogram of cargo into space could be less than $150. As current launch prices are equivalent to about $15,000 per kilogram (to the geosynchronous transfer orbit [GTO]), at such cost a space elevator would have a huge benefit over conventional rockets.

If the operations costs for a space elevator are indeed a low as predicted, then even the development cost may be recovered. Edwards estimates the cost for keeping the first space elevator going for 10 years to be about $300 million—an average of just over $80,000 per day (this is the indirect operations cost—daily costs that are independent of the amount of payload sent up). Assuming a total development cost of $6.2 billion and a payback period of 30 years, then about half a million per day will need to be recovered in addition to the indirect operations cost. At a projected direct operations cost of just $10 per kilogram payload moved up the space elevator, lifting 5000 kg (11,000 pounds) per day at a fee of $145 per kilogram would be sufficient. That would mean a much larger launch market than today, where 5000 kg is put in space on about a weekly basis rather than every day. However, a space elevator will have an enormous effect on the launch market, enabling a much more intensive use of space due to the unprecedented low launch costs.

The satellite launch market situation represents a vicious circle: the launch market will remain small without breakthroughs such as a space elevator, and for such a small market it does not economically make sense to develop expensive new launch systems. As mentioned before, government investment is probably needed to break this loop and develop the first space elevator. Once it is operational and the launch market increases because of its availability, the construction and operation of additional and improved space elevators may become a purely commercial business. At Earth this stage will be difficult to reach, but for space elevators on the Moon and Mars it will be even harder to find an economical balance between costs and benefits.

Unfortunately, no significant amounts of money have been reserved for space elevator development, or the development of any other large tether application, in the current budgets of the world's space agencies. NASA's current post-shuttle and post-International Space Station plans do not include any important space tether mission, and the space agencies of Europe, Russia, Japan, China, and India also do not see space tether development as a priority.

8

Conclusion

Humanity requires more efficient, more sustainable, and much less costly access to space, if it wants to dramatically expand its use of Earth orbit and make interplanetary space part of its economical sphere. We need ways to get into orbit and to reach other planets that do not leave large amounts of debris, require enormous amounts of propellant, or take incredibly long periods of time.

The space tether systems described in this book offer various solutions. Space elevators could provide an easy and regular way to get into Earth orbit, and electrodynamic momentum exchange tethers could send spacecraft from low orbits up to higher ones and vice versa. Tethers could even deorbit return capsules or send spacecraft on their way to other planets. Further out into space, momentum exchange tethers or aerobraking tethers could be used to capture spacecraft into orbits around the Moon, Mars, and Jupiter. Artificial gravity, provided by long spinning tethers, can ease the life of astronauts during their interplanetary travels and counter unwanted physiological changes. To ensure that people can live and work in orbits with too high levels of radiation, electrostatic tethers that sweep away dangerous charged particles around the Earth or even Jupiter may be deployed. Tethers may one day become as invaluable to space travel as chemical rockets today. The 22nd century may see a fleet of spinning tethers strategically placed around Earth, the Moon, and Mars, creating efficient interplanetary highways for spacecraft that require almost no propellant.

The tether applications with potentially the most dramatic impacts are complex and will need large-scale, long, and expensive development. The space elevator requires revolutionary new materials, and all large-scale tethers will exhibit complex dynamics that need to be fully understood to ensure stability and control under all circumstances. Damage protection is an important issue, both in terms of tether materials and concepts and in terms of collision and impact avoidance. There are serious risks associated with having a cable tens of kilometers long rotating in orbit together with other satellites.

M. van Pelt, *Space Tethers and Space Elevators*, DOI: 10.1007/978-0-387-76556-3_8,

The development of large-scale space tether systems will be funded only if the benefits are clear. That means tethers will have to do the job better, more efficiently, and cheaper than competing alternatives such as advanced rocket systems. Projects requiring only modest development durations that promise fast and substantial economic return may be funded by private industries. However, high-cost and high-risk projects with long schedules will need considerable financial support from governments. Political sustainability may be a big issue in that case, because like the Apollo project of the 1960s, the development and construction of an orbital tether infrastructure or space elevator will have to be supported by several successive government administrations.

Space tether development will also require government organizations to set up the right legal frameworks. The current international space treaties that govern rocket launches and orbiting spacecraft are not suited for dealing with space elevators that continually send up cargo or long spinning tethers intersecting many orbits at the same time. As with the construction of the transcontinental railroad in the United States or the current developments in space tourism, government rules and regulations that support innovation will be an essential element of success.

The key to keeping the development of space tethers going appears to be credibility; space tether advocates need to show that their ideas are within the realm of reality and not just science fiction, and that the advantages are real enough to warrant further support from the government and industry. Space tethers will not be developed for their own sake, but to support the ongoing exploration and exploitation of space. Unfortunately, they do not play any role in the current plans that NASA, ESA, and other space agencies have for the near future of space exploration. It will require considerable advocating, publicizing, convincing, and lobbying to keep development going, and that may turn out to be even harder than meeting the technical challenges.

More to Read

As the bibliography at the end of this book indicates, there is a wealth of material available on space tethers. The books mostly focus on the space elevator, and the following are especially recommended:

Arthur C. Clark's classic, *The Fountains of Paradise*, was first published in 1979, but still provides a vivid description of the construction of a space elevator.

Bradley C. Edwards and Eric A. Westling's *The Space Elevator: A*

Revolutionary Earth-to-Space Transportation System details many of the engineering issues related to space elevators. Some basic knowledge of physics and mathematics will be helpful to readers of this book.

LiftPort: Opening Space to Everyone, edited by Bill Fawcett, Michael Laine, and Tom Nugent, Jr., is a book that contains both science-fiction stories and nonfiction articles about space elevators, written by a range of authors. Apart from the basic technical matters, the contributions also examine various financial, legal, social, and political issues.

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