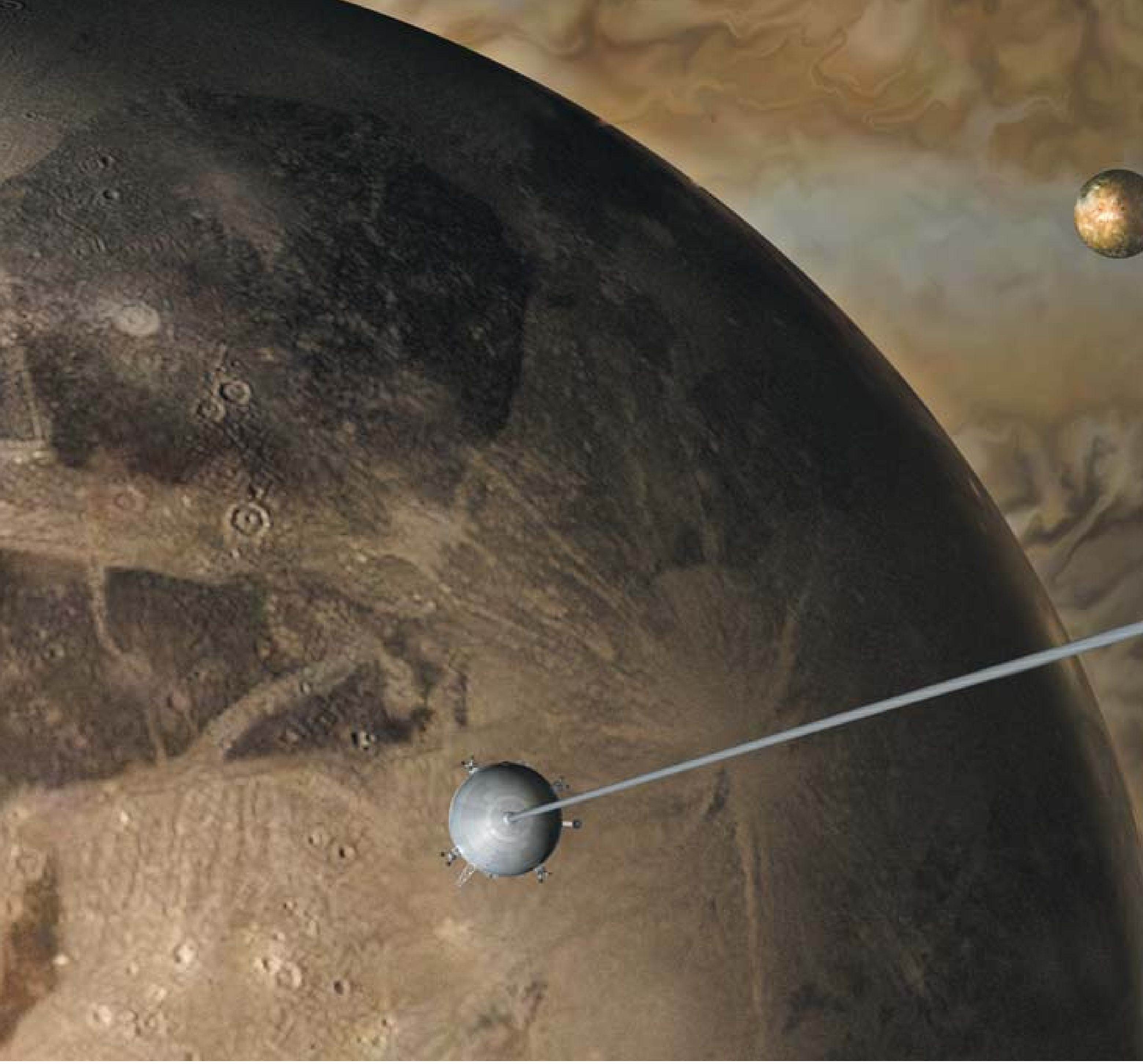
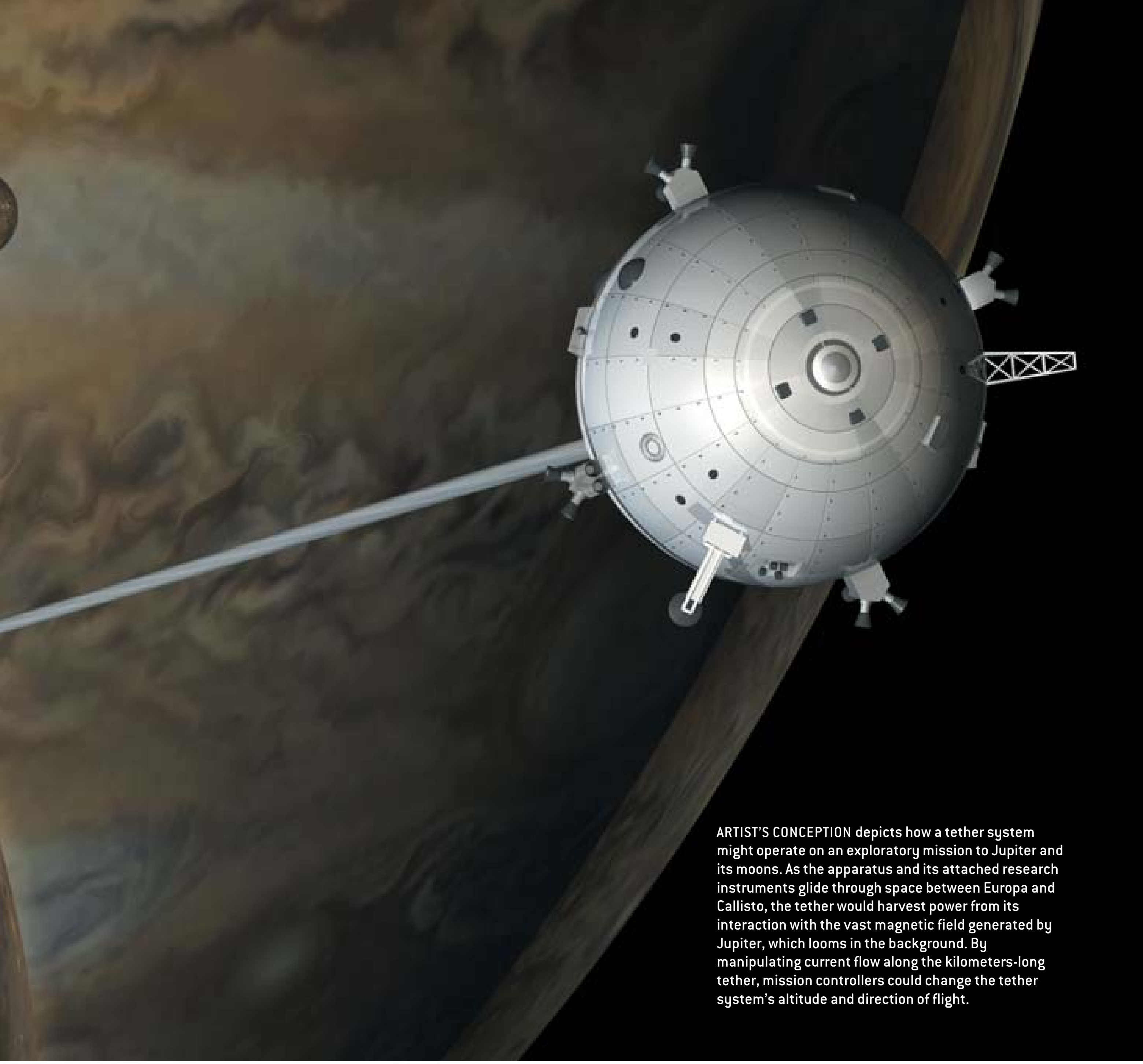


Electrodynamic Tethers in Space

By Enrico Lorenzini and Juan Sanmartín



ARTIST'S CONCEPTION depicts how a tether system might operate on an exploratory mission to Jupiter and its moons. As the apparatus and its attached research instruments glide through space between Europa and Callisto, the tether would harvest power from its interaction with the vast magnetic field generated by Jupiter, which looms in the background. By manipulating current flow along the kilometers-long tether, mission controllers could change the tether system's altitude and direction of flight.

By exploiting fundamental physical laws, tethers may provide low-cost electrical power, drag, thrust, and artificial gravity for spaceflight

There are no filling stations in space.

Every spacecraft on every mission has to carry all the energy sources required to get its job done, typically in the form of chemical propellants, photovoltaic arrays or nuclear reactors.

The sole alternative—delivery service—can be formidably expensive. The International Space Station, for example, will need an estimated 77 metric tons of booster propellant over its anticipated 10-year life span just to keep itself from gradually falling out of orbit. Even assuming a minimal price of $7,000 a pound (dirt cheap by current standards) to get fuel up to the station's 360-kilometer altitude, that is $1.2 billion simply to maintain the orbital status quo. The problems are compounded for exploration of outer planets such as Jupiter, where distance from the sun makes photovoltaic generation less effective and where every gram of fuel has to be transported hundreds of millions of kilometers.

So scientists are taking a new look at an experimentally tested technology—the space tether—that exploits some fundamental laws of physics to provide pointing, artificial gravity, electrical power, and thrust or drag, while reducing or eliminating the need for chemical-energy sources.

Overview/A New Look at Tethers

- Electrodynamic tether systems—in which two masses are separated by a long, flexible, electrically conductive cable—can perform many of the same functions as conventional spacecraft but without the use of chemical or nuclear fuel sources.
- In low Earth orbit, tether systems could provide electrical power and positioning capability for satellites and manned spacecraft, as well as help rid the region of dangerous debris.
- On long-term missions, such as exploration of Jupiter and its moons, tethers could drastically reduce the amount of fuel needed to maneuver while also providing a dependable source of electricity.

Tethers are systems in which a flexible cable connects two masses. When the cable is electrically conductive, the ensemble becomes an electrodynamic tether, or EDT. Unlike conventional arrangements, in which chemical or electrical thrusters exchange momentum between the spacecraft and propellant, an EDT exchanges momentum with the rotating planet through the mediation of the magnetic field [*see illustration on opposite page*]. Tethers have long fascinated space enthusiasts. Visionaries such as Konstantin Tsiolkovsky and Arthur C. Clarke imagined using them as space elevators that whisked people from surface to orbit. In the mid-1960s two of the Gemini flights tested 30-meter tethers as a way to create artificial gravity for astronauts, and numerous kinds of tether experiments have taken place since then. The chief challenges are electromechanical: engineers have not yet devised reliable techniques to deal with the high voltages that EDTs experience in space. Nor have they solved all the issues of tether survivability in the hostile space environment or mastered the means to damp the types of vibrations to which EDTs are prone.

Nevertheless, many scientists believe that the technology could revolutionize some types of spaceflight. Its applications cover low Earth orbit as well as planetary missions. EDTs are likely to find uses around Earth for cleaning up orbital debris and generating electricity at higher efficiency than fuel cells as well as keeping satellites in their desired orbits.

A Self-Adjusting System

TETHERS EXPLOIT the sometimes counterintuitive quirks of orbital mechanics. Two countervailing forces act on any object in a stable orbit around a planet: an outward-pulling centrifugal force produced by orbital motion exactly balances a downward gravitational force. The gravity and centrifugal forces offset each other perfectly at the object's center of mass. An observer onboard is in zero *g*, or free fall, and does not perceive any acceleration.

What happens if, instead of one compact satellite, we have two in slightly different orbits, connected by a tether? The teth-

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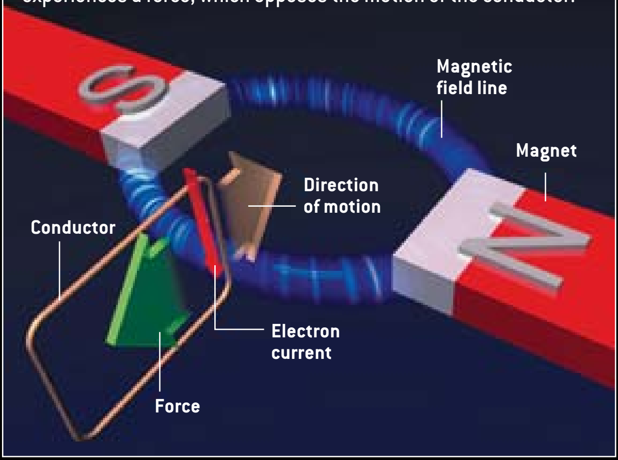
HOW ELECTRODYNAMIC TETHERS WORK

Electrodynamic tether systems have the potential to accomplish many of the same tasks as conventional spacecraft but without the need for large quantities of onboard fuel. They take advantage of two basic principles of electromagnetism: current is produced when conductors move through magnetic fields, and the field exerts a force on the current.

INDUCED CURRENT

When a conductor moves through a magnetic field, charged particles feel a force that propels them perpendicular to both the field and the direction of motion. An electrodynamic tether system uses this phenomenon to generate electric current. The current, in turn, experiences a force, which opposes the motion of the conductor.



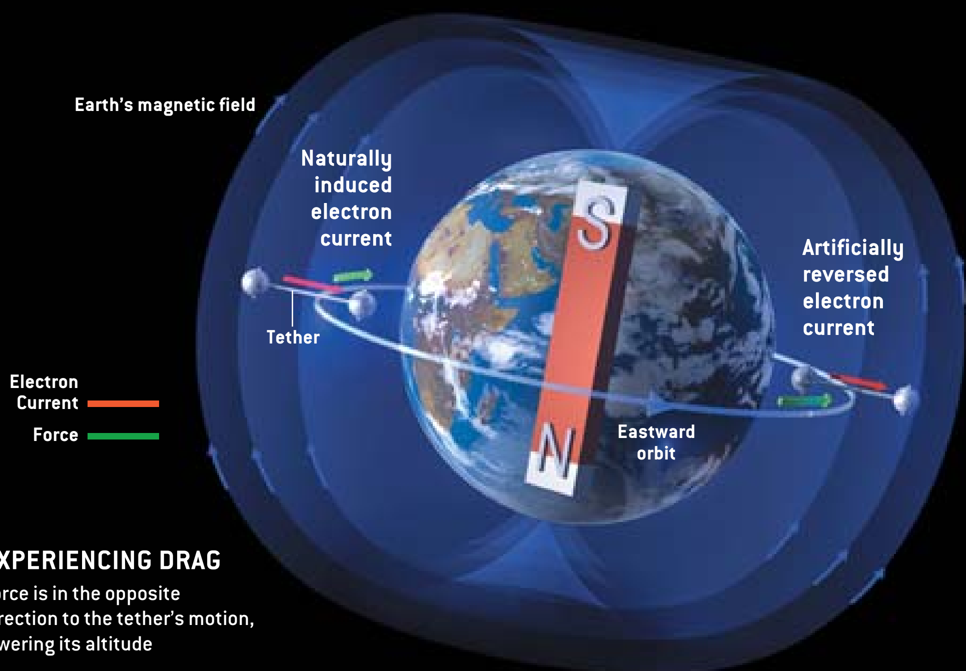
EXTERNALLY DRIVEN CURRENT

A battery added to the circuit can overcome the induced current, reversing the current direction. Consequently, the force changes direction. An electrodynamic tether exploits this effect to produce thrust. (Technical note: These diagrams show the electron current, which is opposite the usual current convention.)

HOW A CURRENT CAN CONTROL TETHER ORBIT

In low orbit, as an electrically conductive tether passes through Earth's magnetic field, an electron current is induced to flow toward Earth (*left*). This current in turn experiences a force from the Earth's field that is opposite the tether's direction of motion. That produces drag, decreasing the tether's energy and lowering its orbit.

Alternatively, reversing the direction of the tether current (using a solar panel or other power source) would reverse the direction of the force that the tether experiences (*right*). In this case, the force would be in the same direction as the tether system's motion, increasing its energy and raising its orbital altitude.



EXPERIENCING DRAG

Force is in the opposite direction to the tether's motion, lowering its altitude

GENERATING THRUST

Force is in the same direction as the tether's motion, raising its altitude

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er causes the two satellites to act as a single system. The gravity and centrifugal forces still balance at the center of mass, halfway between the satellites, but they no longer balance at the satellites themselves. At the outer satellite, the gravity force will be weaker and the centrifugal force stronger; a net force will thus push the satellite outward. The opposite situation occurs at the inner satellite, which is pulled inward.

What is happening is that the lower satellite, which orbits faster, tows its companion along like an orbital water-skier. The outer satellite thereby gains momentum at the expense of the lower one, causing its orbit to expand and that of the lower one to contract. As the satellites pull away from each other, they keep the tether taut. Nonconductive tethers are typically made of light, strong materials such as Kevlar (a carbon fiber) or Spectra (a high-strength polyethylene). Tensions are fairly low, typically from one half to five kilograms for nonrevolving tether systems.

The only equilibrium position of the system is with the tether aligned along the radial direction, called the local vertical. Every time the system tilts away from that configuration, a torque develops that pulls it back and makes it swing like a pendulum. This type of stabilization was used in the Earth-observing satellite GEOS-3 in 1975 to keep the satellite, equipped with a rigid boom several meters long, oriented toward Earth.

Researchers refer to the force imbalance between the two masses as the gravity gradient. Passengers would perceive it as mild gravity pulling them away from Earth on the outer satellite and toward Earth on the inner. In low Earth orbit (LEO, 200 to 2,000 kilometers), a 50-kilometer tether would provide about 0.01 *g* (1 percent of the gravity at Earth's surface). Astronauts would not be able to walk around: a person cannot get sufficient traction at less than 0.1 *g*. But for many purposes (tool use, showers, settling liquids), having a definitive "up" and "down" would obviously be superior to a completely weightless environment. And unlike other techniques for creating artificial gravity, this method does not require that the satellites revolve around each other [*see illustration on opposite page*].

An EDT, employing aluminum, copper or another conductor in the tether cable, offers additional advantages. For one, it serves as an electrical generator: when a conductor moves through a magnetic field, charged particles in the conductor experience an electrodynamic force perpendicular to both the direction of motion and the magnetic field. So if a tether is moving from west to east through Earth's northward-pointing magnetic field, electrons will be induced to flow down the tether [*see illustration on preceding page*].

The tether exchanges electrons with the ionosphere, a region of the atmosphere in which high-energy solar radiation strips electrons from atoms, creating a jumble of electrons and ions, called a plasma. The tether collects free electrons at one end (the anode, or positively charged electron attractor) and ejects them at the opposite end (the cathode, or negatively charged electron emitter). The electrically conductive ionosphere serves to complete the circuit, and the result is a steady current that can be tapped to use for onboard power. As a practical matter, in LEO a 20-kilometer tether with a suitable anode design could produce up to 40 kilowatts of power, sufficient to run manned research facilities.

That capability has been recognized since the 1970s, when Mario Grossi of the Harvard-Smithsonian Center for Astrophysics and Giuseppe Colombo of the University of Padua in Italy were the first to conduct research on EDTs. As many as 16 experimental missions have flown in space using either electrically conductive or nonconductive tethers [*see box on page 57*].

In these early electrodynamic tether systems, a Teflon sleeve fully insulated the conductive part of the tether from the ionosphere, and the anode was either a large conductive sphere or an equivalent configuration to gather electrons. Such anodes, however, turned out to be relatively inefficient collectors. In the 1990s, for example, NASA and the Italian Space Agency jointly launched two versions of the 20-kilometer Tethered Satellite System (TSS). The TSS collected electrons using a metal sphere the size of a beach ball and convincingly demonstrated electrodynamic power generation in space. Despite those positive results, however, researchers discovered a difficulty that must be overcome before EDTs can be put to practical use. A negative net charge develops around a large spherical anode, impeding the flow of incoming electrons much as a single exit door creates a pileup of people when a crowd rushes to leave a room.

One of us (Sanmartín) and his colleagues introduced the bare-tether concept to solve this problem. Left mostly uninsu-

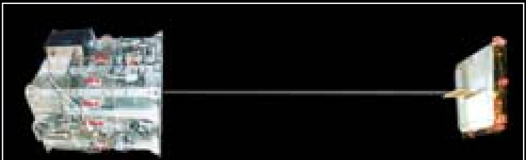
> *Visionaries imagined* using space tethers as space elevators that whisked *people from surface to orbit.*

THE AUTHORS

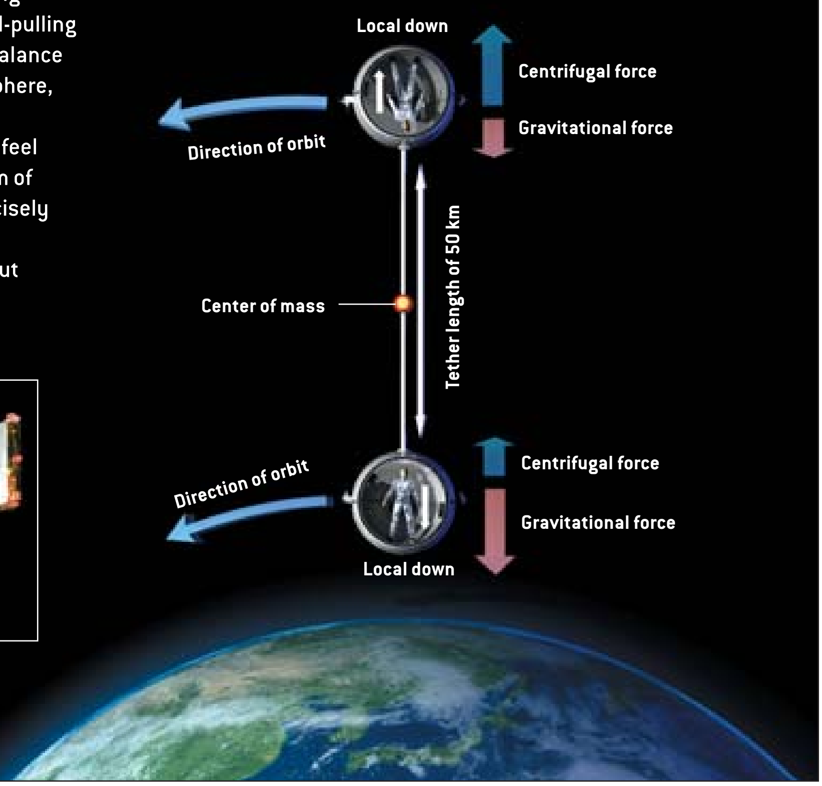
ENRICO LORENZINI and *JUAN SANMARTÍN* have worked together for a decade on tether projects. Lorenzini is a space scientist at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass., where, since 1995, he has led the research group of the late pioneers of space tethers Mario Grossi and Giuseppe Colombo. In 1980 he received his doctorate in aeronautics from the University of Pisa in Italy. Sanmartín has been professor of physics at the Polytechnic University of Madrid in Spain since 1974. Before that, he worked at Princeton University and the Massachusetts Institute of Technology. He has doctoral degrees from the University of Colorado and the Polytechnic University of Madrid.

ARTIFICIAL GRAVITY FROM A TETHER

For any object in a stable orbit, the outward-pushing centrifugal force is exactly balanced by the inward-pulling gravitational force. In a tether system, all forces balance at the system's center of mass. But at the outer sphere, the centrifugal force is slightly larger than the gravitational force. As a result, a passenger would feel a slight "downward" force away from Earth—a form of artificial gravity (local down). The situation is precisely reversed for the inner sphere. For a system with a 50-kilometer-long tether, the force would be about 1/100 the magnitude of Earth's gravity. The force is approximately proportional to the tether length.



COMPOSITE PHOTOGRAPH of an actual tether system, called ATEx, shown in its semideployed state.



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lated, the tether itself collects electrons over kilometers of its length rather than just at the tip. The tether benefits further from its thin, cylindrical geometry: electrons do not have to bunch up at one anode point, where their collective negative charge inhibits the arrival of more electrons. It need not be a round wire; a thin tape would collect the same current but would be much lighter.

A Nearly Free Lunch

ALL EDTS SHARE an advantage: they can reduce or increase their velocity while in orbit by exploiting a fundamental principle of electromagnetism. A magnetic field exerts a force on a current-carrying wire according to the familiar "right-hand rule." Thus, for an EDT in eastward LEO, in which the electrons flow from top to bottom of the tether, the force is opposite to the direction of motion. The EDT experiences a resistance akin to air drag, which in turn lowers the tether system's orbit.

That may not seem like a desirable feature. But it is extremely attractive to planners concerned with sweeping up the large amount of space junk that now circles the planet in the form of dead satellites and spent upper stages of rockets. Indeed, the problem has been one of the motivations behind the development of tethers by NASA, universities and small companies. At present, LEO is littered with several thousands of such objects, about 1,500 of which have a mass of more than 100 kilograms. Eventually atmospheric drag removes them from orbit by lowering their altitudes until they burn up on reentry into the dense lower atmosphere. Typically objects at an orbital altitude of 200 kilometers decay in several days, those at 400 kilometers in several months, and those at 1,000 kilometers in about 2,000 years.

If newly launched satellites carried EDTs that could be deployed at the end of their lifetimes, or if a robot manipulator could capture debris and carry it to an orbiting tether system, the drag effect could be used to speed up the reentry timetable [*see illustration on next page*]. Conversely, reversing the direction of the current in an EDT in low Earth orbit (by using a photovoltaic array or other power supply) would produce the opposite effect. The tether system would experience a force in its direction of motion, yielding thrust instead of drag and raising its orbit. Propulsive EDTs could thus serve as space tugs to move payloads in LEO to a higher orbit or to counteract orbital decay. Recall the International Space Station's high-cost boost problem. If the ISS had employed an electrodynamic tether drawing 10 percent of the station power, it would need only 17 tons of propellant (as opposed to 77 in the current design) to avoid orbital decay; more power would nearly eliminate the need for propellant. Also, switching on a propulsive EDT at the right time along the orbit can produce lateral forces useful for changing the inclination of any spacecraft in orbit—an operation that requires a large amount of fuel when it is carried out with chemical thrusters.

Of course, conservation of energy demands that there is no "free lunch." For instance, power is generated only at the expense of the satellite's altitude, which was originally achieved by expending energy in rocket engines. So it may seem at first glance as if EDTs merely exchange one kind of energy for another in a rather pointless exercise. In drawing power from the tether, the satellite would descend and require reboosting. A fuel cell, in contrast, converts fuel into electricity directly. So why bother?

The answer is that the tether system is potentially more efficient, however paradoxical it may appear. The combination tether/rocket can generate more electrical power than a fuel cell can because the cell does not profit from the orbital energy of its fuel, whereas the tether/rocket does. In an EDT, the electrical power produced is the rate of work done by the magnetic drag—that is, the magnitude of the drag force times the velocity of the satellite (relative to the magnetized ionosphere), which is about 7.5 kilometers per second in LEO. By comparison, the chemical power generated by a rocket equals one half the thrust times the exhaust velocity. A mixture of liquid hydrogen and liquid oxygen produces an exhaust with a speed as high as five kilometers per second. In practical terms, therefore, a tether/rocket combination could generate three times as much electrical power as the chemical reaction alone produces. A fuel cell, which also uses hydrogen and oxygen, has no such advantage.

The combination tether/rocket might consume substantially less fuel than a fuel cell producing equal power. The tradeoff is that the tether is heavier than the fuel cell. Thus, use of a tether to generate power will result in overall savings only for a period longer than five to ten days.

Tethers, by Jove

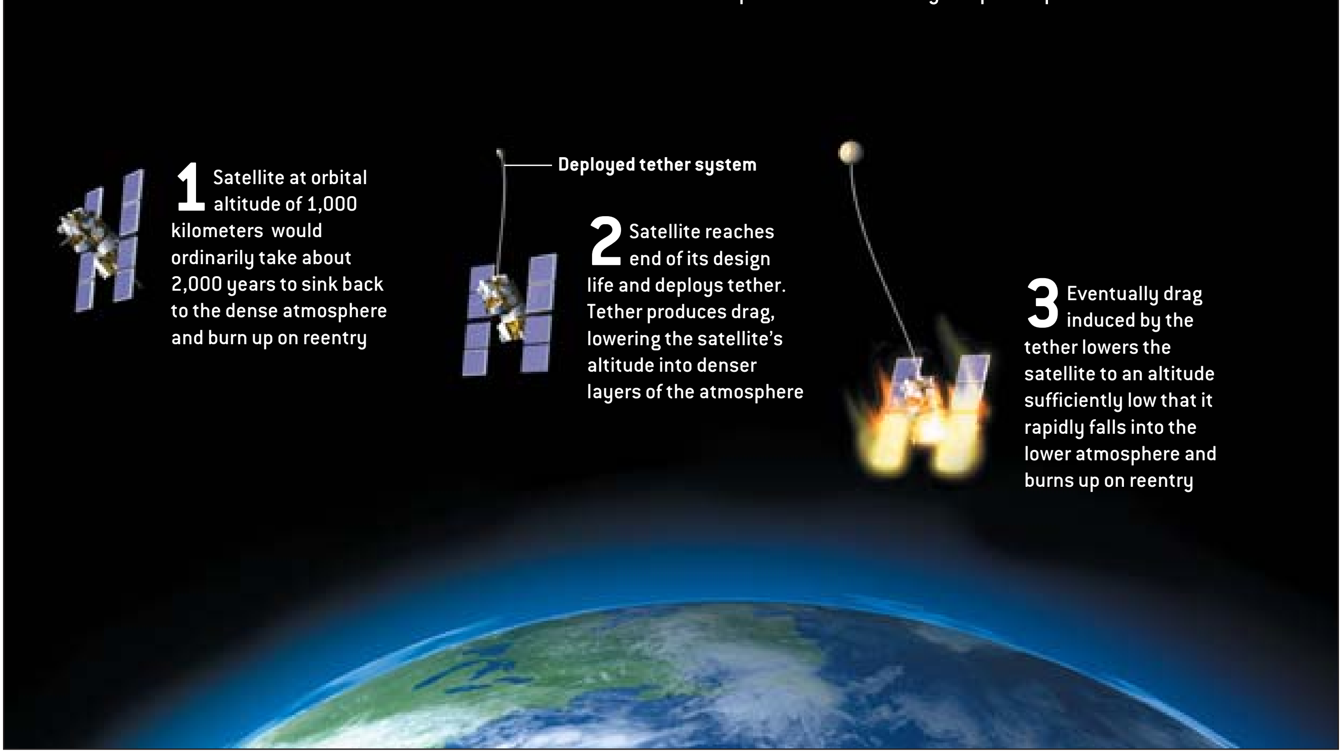
IN CERTAIN CIRCUMSTANCES, such as a mission to explore Jupiter and its moons, tether systems have further advantages. By exploiting the giant planet's physical peculiarities, a tether system could eliminate the need for enormous amounts of fuel. Like Earth, Jupiter has a magnetized ionosphere that rotates with the planet. Unlike Earth, its ionosphere persists beyond the stationary orbit—the altitude at which a given object remains above the same location on the planet's surface. For Earth, that is about 35,800 kilometers; for Jupiter, about 88,500 kilometers above the cloud tops.

In a Jovian stationary orbit, a spacecraft goes around the planet at the same speed as the ionosphere. So if the spacecraft descends below stationary altitude, where the speed of the magnetized plasma is lower than the speed of the spacecraft, the natural output of an EDT is a drag force, along with usable electrical power from the tether current. Alternatively, above the stationary orbit, where the magnetized plasma moves faster than the spacecraft, the natural result is thrust and usable electrical power.

USING TETHERS TO REMOVE OBJECTS FROM ORBIT

The region of low Earth orbit—from 200 to 2,000 kilometers above the surface—has become littered with tens of thousands of objects, including defunct satellites, rocket motors, explosion debris and miscellaneous hardware.

It takes decades to centuries for these objects to sink into the lower atmosphere, where they are incinerated by air friction. Deploying tethers on newly launched spacecraft would provide a simple and low-cost way to speed up that timetable.



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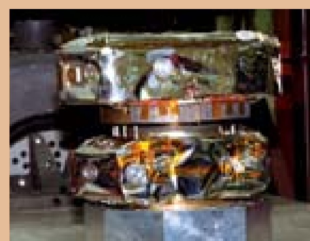
TETHERED MISSIONS

Researchers have launched experimental tether systems for decades, with varying degrees of success. Sometimes the tethers could not extend to their full lengths. But even problematic flights have confirmed the capabilities of tether systems and led to numerous design improvements. Missions that used electrodynamic tethers are indicated in brown.

NAME	DATE	ORBIT	LENGTH	AGENCY
Gemini 11	1967	LEO	30 m	NASA
Gemini 12	1967	LEO	30 m	NASA
H-9M-69	1980	Suborbital	< 500 m	NASA
S-520-2	1981	Suborbital	< 500 m	NASA
Charge-1	1983	Suborbital	500 m	NASA/Japanese ISAS
Charge-2	1984	Suborbital	500 m	NASA/Japanese ISAS
Oedipus-A	1989	Suborbital	958 m	Canadian NRC/NASA
Charge-2B	1992	Suborbital	500 m	NASA/Japanese ISAS
TSS-1	1992	LEO	< 500 m	NASA/Italian Space Agency
SEDS-1	1993	LEO	20 km	NASA
PMG	1993	LEO	500 m	NASA
SEDS-2	1994	LEO	20 km	NASA
Oedipus-C	1995	Suborbital	1 km	Canadian NRC/NASA
TSS-1R	1996	LEO	19.6 km	NASA/Italian Space Agency
TiPS	1996	LEO	4 km	NRO/NRL
ATEx	1999	LEO	6 km	NRL


ATEx


TiPS

Again, this might appear to be a free-lunch scenario. But it is not. The energy is taken from the planet's rotation in both cases. Jupiter's collective momentum, however, is so vast that the tiny amount expended on the spacecraft is negligible.

According to the principles of orbital dynamics, the most efficient places to apply drag or thrust are the points in the orbit nearest (periapsis) and farthest (apoapsis) from Jupiter. The natural force will be drag if the point lies inside the stationary orbit and thrust if it lies outside. Assume that a tether-bearing spacecraft would approach Jupiter with a relative velocity of about six kilometers per second. If drag were not applied, the spacecraft would fly past Jupiter. But if the tether were turned on as the spacecraft came inside the stationary orbit, it could brake the motion just enough to put the spacecraft in an elongated, highly eccentric ellipse around Jupiter. Capture into such an orbit requires reducing the velocity by only hundreds of meters per second. A tether tens of kilometers long would suffice.

As the spacecraft went around and around Jupiter, mission controllers would turn on the tether near periapsis to produce drag (and usable power) and turn it off elsewhere. That gradually would reduce the orbit from an elongated ellipse to smaller, progressively more circular shapes. The spacecraft would then require only modest electrodynamic forces to visit each of the four largest moons of Jupiter, from the outermost (Callisto) to the innermost (Io). With Callisto's orbital period of about half a month, the entire sequence could take less than a year.

To return, controllers would reverse the process. They would first switch on the EDT at apoapsis, which lies outside the stationary orbit, to produce thrust and power. The repeated thrust applications at apoapsis would raise periapsis from inside to outside the stationary orbit. Now thrust could be generated (for "free" again) at periapsis, progressively increasing the altitude of apoapsis. A final push could boost the spacecraft out of orbit for transfer back to Earth. Tapping Jupiter's rotation would provide all the energy for these maneuvers as well as generate usable power. By reducing drastically the fuel and power requirements, the tether would greatly cut the cost of a mission.

The technology of space tethers has matured tremendously in the past 30 years. But it still faces several challenges before EDTs can be put to practical use in orbit around Earth, Jupiter or elsewhere. Designers will have to devise ways to protect tethers from the effects of the high electrical potential between the tether and the ionosphere as well as from the slow degradation of materials in space. And they must learn to control the various vibrations that arise in electrodynamic tether systems. These obstacles are not insuperable, however, and many scientists expect to see tethers doing real work in orbit in the not so distant future. SA

MORE TO EXPLORE

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