ROCKETS ARE GETTING US NOWHERE FAST.

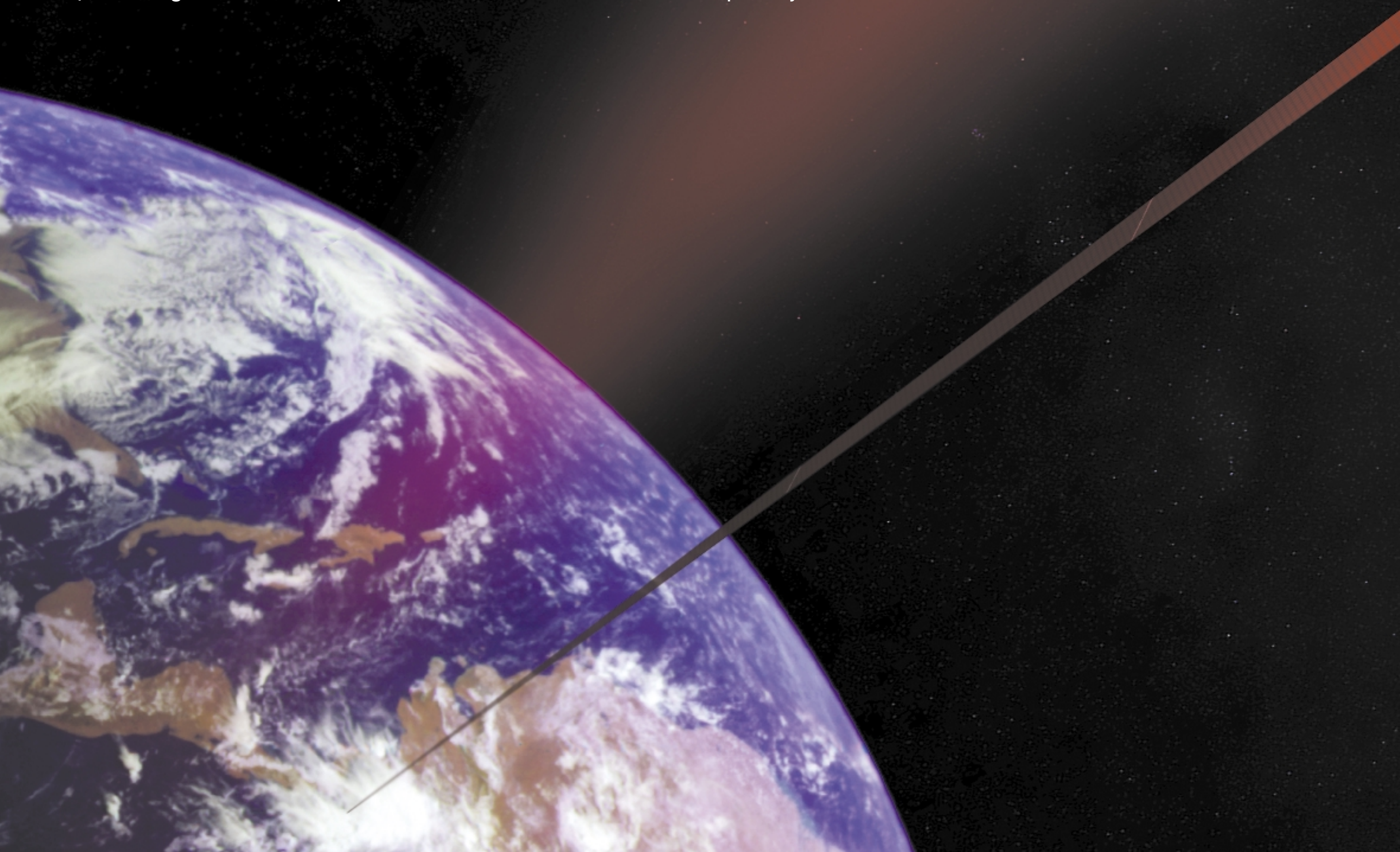
Since the dawn of the space age, the way we get into space hasn't changed: we spend tens or hundreds of millions of dollars on a rocket whose fundamental operating principle is a controlled chemical explosion. We need something better, and that something is a space elevator—a superstrong, lightweight cable stretching 100 000 kilometers from Earth's surface to a counterweight in space. Roomy elevator cars powered by electricity would speed along the cable. For a fraction of the cost, risk, and complexity of today's rocket boosters, people and cargo would be whisked into space in relative comfort and safety.

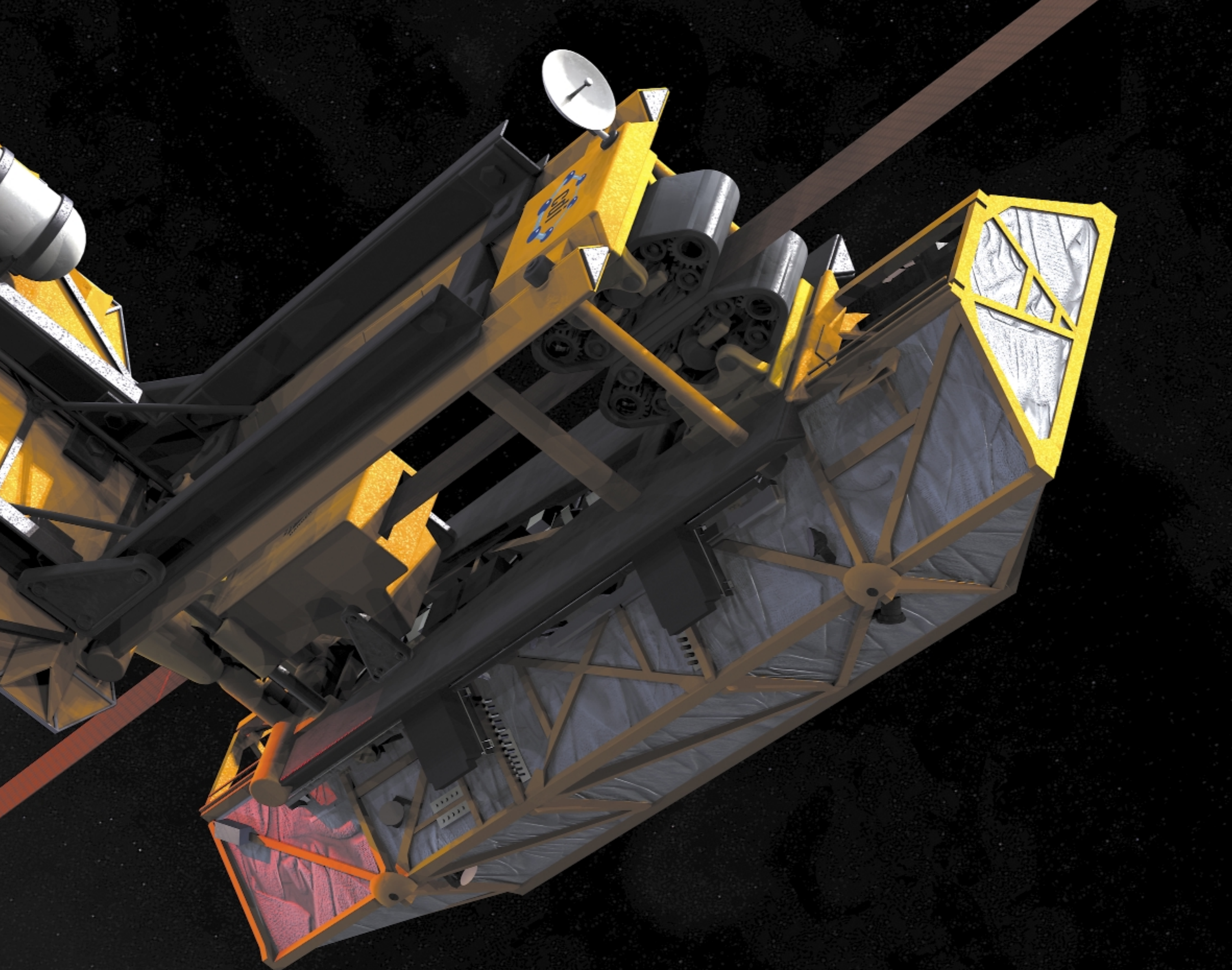
It sounds like a crazy idea, and indeed the space elevator has been the stuff of science fiction for decades. But if we want to set the stage for the large-scale and sustained exploration and colonization of the planets and begin to exploit solar power in a way that could significantly brighten the world's dimming energy outlook, the space elevator is the only technology that can deliver.

It all boils down to dollars and cents, of course. It now costs about US $20 000 per kilogram to put objects into orbit. Contrast that rate with the results of a study I recently performed for NASA, which concluded that a single space elevator could reduce the cost of orbiting payloads to a remarkably low $200 a kilogram and that multiple elevators could ultimately push costs down below $10 a kilogram. With space elevators we could eventually make putting people and cargo into space as cheap, kilogram for kilogram, as airlifting them across the Pacific.

The implications of such a dramatic reduction in the cost of getting to Earth orbit are startling. It's a good bet that new industries would blossom as the resources of the solar system became accessible as never before. Take solar power: the idea of building giant collectors in orbit to soak up some of the sun's vast power and beam it back to Earth via microwaves has been around for decades. But the huge size of the collectors has made the idea economically unfeasible with launch technologies based on chemical rockets. With a space elevator's much cheaper launch costs, however, the economics of space-based solar power start looking good.

A host of other long-standing space dreams would also become affordable, from asteroid mining to tourism. Some of these would depend on other space-transportation technologies for hauling people and cargo past the elevator's last stop in high-Earth orbit. But physics dictates that the bulk of the cost is dominated by the price of getting into orbit in the first place. For example, 95 percent of the mass of each mighty Saturn V moon rocket was used up just getting into low-Earth orbit. As science-fiction author Robert A. Heinlein reportedly said:





A Hoist to the HEAVENS

A space elevator could be the biggest thing to happen since the Stone Age, but can we build one?

BY BRADLEY CARL EDWARDS

ALL ILLUSTRATIONS: ALAN CHAN

"Once you get to Earth orbit, you're halfway to anywhere in the solar system." With the huge cost penalty of traveling between Earth and orbit drastically reduced, it would actually be possible to quarry mineral-rich asteroids and return the materials to Earth for less than what it now costs, in some cases, to rip metal ores out of Earth's crust and then refine them. Tourism, too, could finally arrive on the high frontier: a zero-gravity vacation in geostationary orbit, with the globe spread out in a ceaselessly changing panoply below, could finally become something that an average person could experience. And for the more adventurous, the moon and Mars could become the next frontier.

SO WHY CAN'T WE DO ALL THIS with rockets? And why is the space elevator so cheap?

The answer is that chemical rockets are inherently too inefficient: only a tiny percentage of the mass at liftoff is valuable payload. Most of the rest is fuel and engines that are either thrown away or recycled at enormous expense. Nuclear and electric rockets promise huge improvements in efficiency and will be vital to the future of solar system exploration, but they are impractical as a means of getting off Earth: they either don't produce enough thrust to overcome gravity or pose a potentially serious radiation hazard.

On the other hand, space elevators could haul tons of material into space all day, every day. And the core of the space elevator—the cable—could be constructed from cheap, plentiful materials that would last for decades.

A space elevator would be amazingly expensive or absurdly cheap—depending on how you look at it. It would cost about $6 billion in today's dollars just to complete the structure itself, according to my study. Costs associated with legal, regulatory, and political aspects could easily add another $4 billion, but these expenses are much harder to estimate.

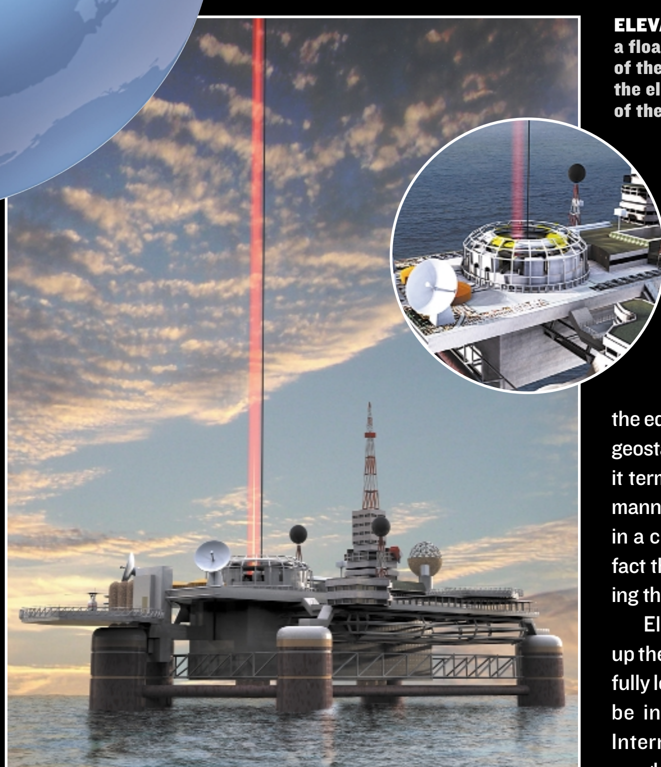
Building such an enormous structure would probably require treaty-level negotiations with the international community, for example. A $10 billion price tag, however, isn't really extraordinary in the economics of space exploration. NASA's budget is about $15 billion a year, and a single shuttle launch costs about half a billion dollars.

The construction schedule could conceivably be as short as 10 years, but 15 years is a more realistic estimate when technology development, budget cycles, competitive selection, and other factors are accounted for.

After the first elevator was built, its initial purpose would be to lift into space the materials for a second elevator. As with conventional elevators in tall buildings, practical realities make it almost certain that more than one elevator would be constructed. With separate "up" and "down" elevators, you could haul cargo and passengers simultaneously to and from space. The second elevator would be much easier and cheaper to build than the first, not only because it could make use of the first elevator but because all the R&D and much of the supporting infrastructure would already be complete. With these savings, I estimate that a second elevator would cost a fraction of the first one—as little as $3 billion dollars for parts and construction.

In my studies, I have found that the schedule for more elevators, after the first, could be compressed to as little as six months. The first country or consortium to finish an elevator would therefore gain an almost unbeatable head start over any competitors.

WATCHING THE SKIES: A ground-based array of radar dishes would be used to detect orbiting objects as small as 1 centimeter in diameter that could pose a threat to the elevator cable.



ELEVATOR AHOY: The space elevator would be anchored to Earth by a floating platform, located on the equator several hundred kilometers west of the Galápagos Islands. The platform would also house lasers used to power the elevator cars. Its mobility would allow the elevator cable to be moved out of the way of orbiting objects.

PHOTO: NASA/JET PROPULSION LABORATORY

The estimated operational cost for the first elevator is several hundred dollars per kilogram to any Earth orbit, the moon, or Mars, a drop of two orders of magnitude over the cost of current launch technologies. With the completion of subsequent elevators, the cost would drop even further, to a few dollars per kilogram.

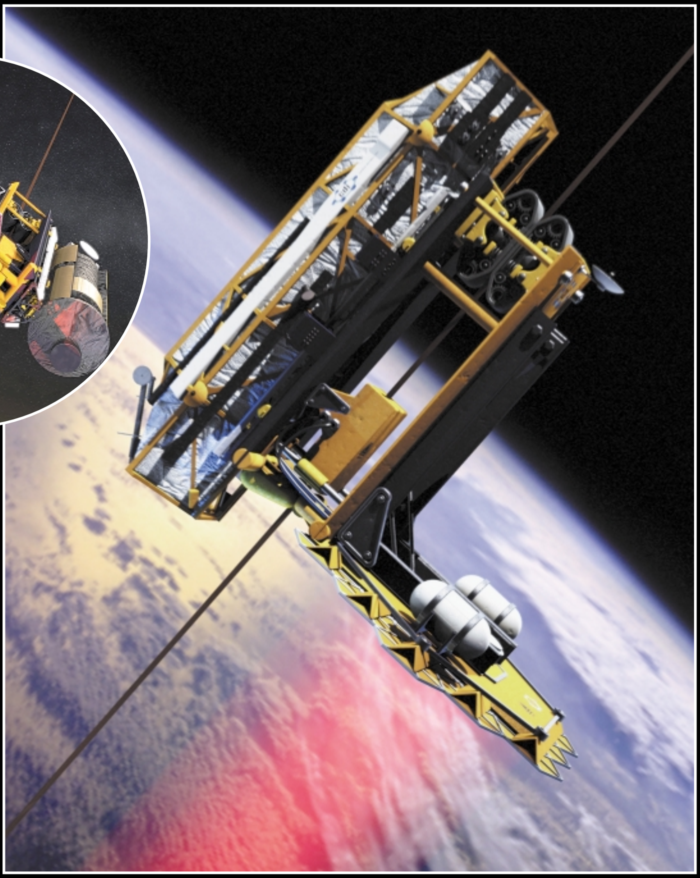
So how exactly would it work? Springing out from an anchor point on the equator, the space elevator cable would rise straight up, passing through geostationary orbit at 36 000 km and continuing for another 64 000 km until it terminates in a 600-ton counterweight. The cable would be held up in a manner similar to that which holds a string taut as a weight tied to it is swung in a circle. The key detail that would make the elevator work would be the fact that its center of gravity would be at the geostationary orbit mark, forcing the entire structure to move in lockstep with Earth's rotation.

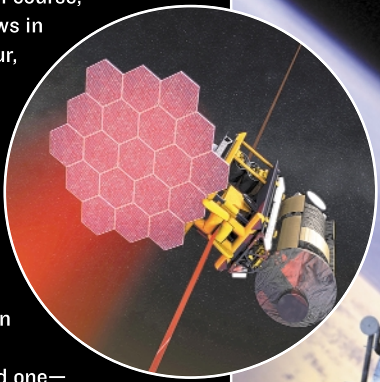
Electrically powered elevator cars, which I call climbers, would crawl up the cable, carrying people or cargo. Each car would weigh about 20 tons fully loaded, of which about 13 tons would be payload. These payloads could be in the form of inflatable structures, like those proposed for the International Space Station, with about 900 cubic meters of space, or roughly as much as a five-bedroom house. For passengers, a climber would be like a space-going cruise ship; there would be small sleeping quarters, a tiny kitchen and other amenities, and, of course, windows with some of the most stunning views in the solar system. Ascending at 190 km per hour, the climbers would reach geostationary orbit in about eight days [see illustration, "Way Station"].

THE BIGGEST CHALLENGES to building an elevator are finding a strong enough cable material and then designing and constructing the cable. The cable would be the heart of the elevator, and finding the right stuff for its manufacture has historically been the main obstacle to turning the elevator into reality.

In fact, the space elevator concept is an old one—Russian scientist Konstantin Tsiolkovsky proposed the basic concept more than a century ago. The idea resurfaced in the 1960s, but at the time there was no material in existence strong enough for the cable. To support its own weight as well as the weight of climbers, the cable has to be built out of something that is incredibly light and yet so strong that it makes steel seem like soft-serve ice cream. The space elevator faded back into the realm of sci-fi.

Then, in 1991, Japanese researcher Sumio Iijima discovered carbon nanotubes. These are long, narrow, cylindrical molecules; the cylinder walls are made of carbon atoms, and the tube is about 1 nanometer in diameter.

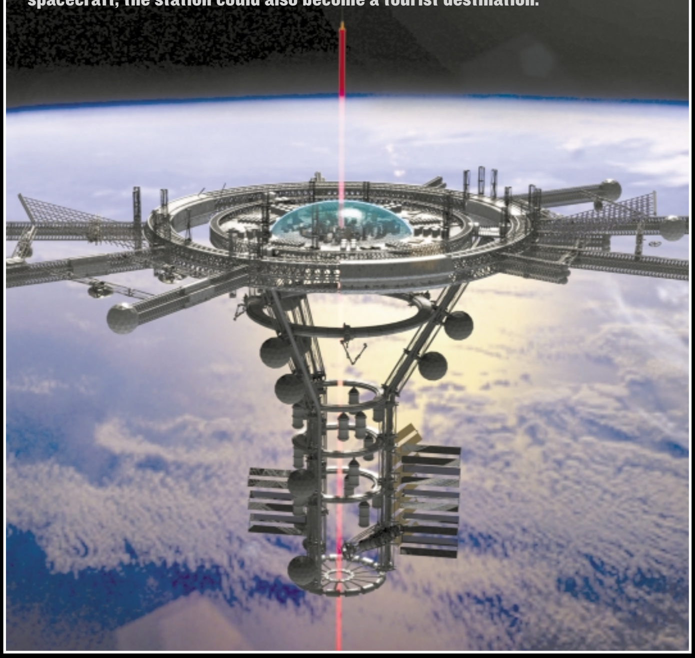




GOING UP: The elevator cars would be powered using photovoltaic cells [inset] tuned to the wavelength of a ground-based laser, and would climb the elevator cable by gripping it between treads. Each 20-ton climber would be able to haul about 13 tons of payload into space, which could either be simple cargo pallets or inflatable habitats designed to lift humans to geostationary orbit in about eight days.

30 000 km — 36 000 km — 40 000 km — 50 000 km

WAY STATION: Over time, a substantial transfer station would be built at geostationary orbit, 36 000 kilometers up the cable. In addition to deploying satellites into other orbits, handling cargo, and even assembling or refueling spacecraft, the station could also become a tourist destination.



In theory, at least, carbon-nanotube-based materials have the potential to be 100 times as strong as steel, at one-sixth the density. This strength is three times as great as what is needed for the space elevator. The most recent experiments have produced 4-centimeter-long pieces of carbon-nanotube materials that have 70 times the strength of steel. Outside the lab, bulk carbon-nanotube composite fibers have already been made in kilometer-long lengths, but these composite fibers do not yet have the strength needed for a space elevator cable.

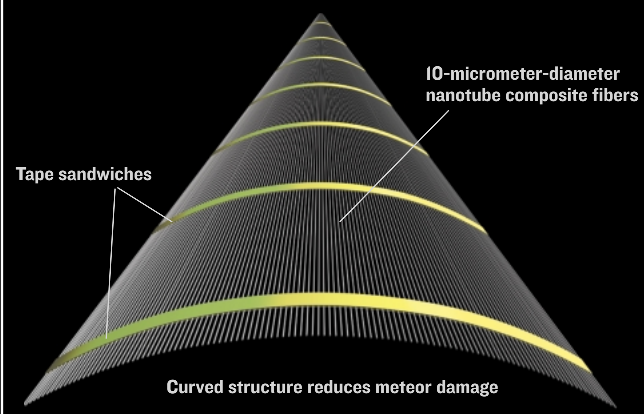
However, we think we know how to get there. There are two methods being examined at academic institutions and at my company, Carbon Designs Inc., in Dallas. The first approach is to use long composite fibers, which are about as strong as steel and have a composition of 3 percent carbon nanotubes, the rest being a common plastic polymer. By improving the ability of the carbon-nanotube wall to adhere to other molecules and increasing the ratio of nanotubes to plastic in the fiber to 50 percent, it should be possible to produce fibers strong enough for the space elevator cable.

The second approach is to make the cable out of spun carbon-nanotube fibers. Here, long nanotubes would be twisted together like conventional thread. This method has the potential to produce extremely strong material that could meet the demands of the space elevator. Both processes could be proved in the next few years.

With a suitable material on the horizon, the next question is the design of the cable itself. Prior to 2000, in both science fiction and the scant technical literature, the space elevator was a massive system—with huge cables 10 meters in diameter or inhabited towers more than a kilometer across. These systems also required snagging asteroids to use as the counterweight at the end of the elevator. Suffice it to say, it's all well beyond our current engineering capabilities—mechanical, electrical, material, and otherwise.

IN MY STUDY, I sought a design that could be built soon and could annually lift 1500 tons, or 10 times as much mass as the United States now launches into space in a typical year. In 2000, I received a grant from NASA's Institute for Advanced Concepts to begin a new study on space elevators. The study formed the basis of a book I coauthored with Eric A. Westling, *The Space Elevator: A Revolutionary Earth-to-Space Transportation System* (Spageo Inc., 2002). Work continued at the

CABLE CLOSE-UP: The 100 000-kilometer-long elevator ribbon would be made up of strands of carbon-nanotube-based fibers. Even if a strand were broken, its load would be safely redistributed among the other fibers.



leads us to the other big problem in building the elevator: how would we get all that cable and counterweight mass up into space in the first place?

Currently, the largest rockets available can place only a 5-ton payload into the 36 000-km geostationary orbit where construction would have to begin. Remember that to keep the elevator fixed above one spot on Earth's surface, its center of gravity must always remain at the 36 000-km mark.

Launching and assembling hundreds of 5-ton payloads would be impractical, so my colleagues and I devised an alternative plan. An initial "deployment spacecraft" and two smaller spools of ribbon massing 20 tons each would be launched separately into low-Earth orbit using expendable rockets. The deployment spacecraft and spools would be assembled together using techniques pioneered for the Mir space station and the International Space Station. The deployment spacecraft would then follow a spiral course out to geostationary orbit using a slow, but fuel-efficient, trajectory.

Upon arrival, the spacecraft would begin paying out the two spools side by side toward Earth. Meanwhile, the deployment spacecraft would fire its engine again, raising it above geostationary orbit. The spacecraft's motions would be synchronized with the unreeling cable so that the spacecraft would act as the counterweight to the rest of the cable: this would keep the center of gravity of the entire elevator structure in geostationary orbit [see illustration, "View From the Top"]. When the two halves of the ribbon reached Earth's surface, a special elevator car would be attached that would ascend the elevator, stitching the two side-by-side halves of the ribbon together. This initial system would have a 20-cm-wide ribbon and could support 1-ton climbers.

Other specialized climbers would then be sent up this initial ribbon, adding more small ribbons to the existing one. When one reached the far end of the elevator cable, the climber's mass would be added to the counterweight, keeping the elevator in balance so that its center of gravity would stay in geostationary orbit. After 280 such climbers, a meter-wide ribbon that could support 20-ton climbers would be complete.

50 000 km 60 000 km 70 000 km

FIVE YEARS AGO, THE SPACE ELEVATOR WAS CONSIDERED SCIENCE FICTION BY MOST OF THE SPACE COMMUNITY. WITH THE ADVENT OF CARBON-NANOTUBE COMPOSITES AND THE CONCLUSIONS OF RECENT STUDIES, THE SPACE ELEVATOR CONCEPT IS MOVING TOWARD MAINSTREAM ACCEPTANCE

Institute for Scientific Research Inc., in Fairmont, W. Va., and now at Carbon Design. The result is a preliminary design for a simplified, cheaper, and lightweight elevator.

This design calls for a ribbon instead of a round cable. The flexible ribbon, just 1 meter wide and thinner than paper, would be made of carbon-nanotube composite fibers arranged in long strands, cross-braced to evenly redistribute the load if a strand were cut. Space debris that would sever a small round cable would pass through the broader ribbon, creating small holes and a manageable reduction in cable strength, letting it survive impacts from small debris and meteoroids, which would be fairly common [see image, "Cable Close-Up"].

Choosing a ribbon rather than a circular cable also greatly simplifies the design of the tread system for moving the elevator car along the cable. The climbers would pull themselves up the cable using pairs of motorized treads that clamp the cable between them. The broad, flat treads would sandwich the ribbon, exerting significant forces against each other to grip the cable securely. The treads are based on conventional treads, the drive system is built with fairly standard dc electric motors, and the control systems are no more complex than what you'd find in a typical auto today. A round cable, on the other hand, would require a far more complex arrangement of wheeled gripping systems.

Because of the thinness of the ribbon, it would be surprisingly light: the entire 100 000-km length would have a mass of just 800 tons, not counting the counterweight's 600 tons. But this is still obviously substantial, and it

The climbers, like most of the elevator system, would use off-the-shelf components wherever possible. One of the reasons the climbers would be so simple and have so much room for payload is that they would not carry power-generating equipment. Power would be delivered to climbers by lasers beaming 840-nm light from Earth onto an array of photovoltaic cells; at this wavelength, photovoltaic cells can generate electricity at an efficiency of 80 percent [see illustration, "Going Up"]. The lasers required are not yet available, but components are being tested, and free-electron or solid-state lasers at the power levels we need (hundreds of kilowatts) are expected to be available in a few years.

ONCE AN ELEVATOR IS DEPLOYED, keeping it operating would be the next big challenge. Serious threats to an elevator would come from:

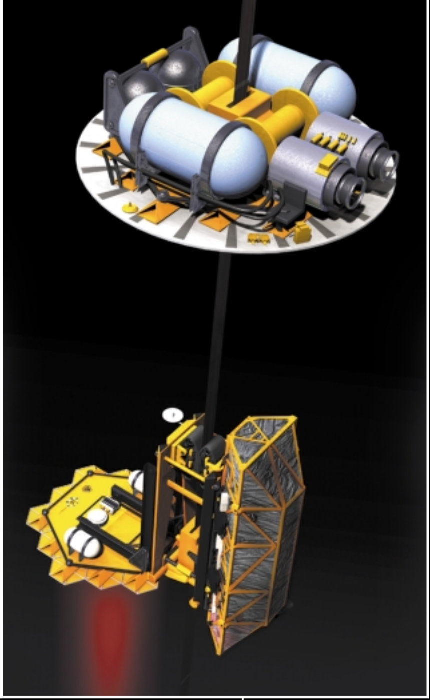
- The weather—lightning, wind, hurricanes, tornadoes, and jet streams
- Airplanes, meteors, space debris, and satellites
- Erosion from atomic oxygen in the upper atmosphere
- Radiation damage
- Induced oscillations in the cable
- Induced electrical currents
- Terrorists

Some of these challenges would be met merely by locating the elevator's Earth anchor in the eastern equatorial Pacific, west of the Galápagos Islands, where the weather is unusually calm and the threats from hurricanes, tornadoes, lightning, jet streams, and wind are greatly reduced. This location is also about 650 km from any current air routes or sea lanes, significantly reducing the chance of an accidental collision and making the site easier to secure against terrorists. An anchor in the Pacific obviously implies a floating platform, but such structures are already commercially available, thanks to the offshore oil industry [see illustration, “Elevator Ahoy”].

These platforms would be mobile, which would allow the elevator, with sufficient warning, to avoid orbiting satellites and debris by moving the anchor end of the cable back and forth about 1 km, pulling the ribbon out of the path of an oncoming object. While debris and other objects down to 10 cm in diameter are currently tracked, objects with diameters as small as 1 cm are a potential threat to the elevator. As a consequence, the current elevator system design includes a high-sensitivity ground-based radar facility to track all objects in low-Earth orbit that are at least 1 cm wide [see illustration, “Watching the Skies”]. A system like this was designed for the International Space Station but never implemented.

Eliminating erosion from atomic oxygen at altitudes of 100 to 800 km would be the job of thin metal coatings applied to the cable. Radiation damage would be mitigated by using carbon nanotubes and plastic polymer materials that are inherently radiation resistant.

VIEW FROM THE TOP: At the end of the elevator would be the counterweight, which would keep the elevator's center of gravity at the geostationary orbit mark. Initially, the counterweight would be the deployment spacecraft used to put the cable into orbit, and used elevator cars would be added to its mass.



Of course, the cable below the severed point would fall. But because the linear density of the ribbon would be just 8 kg/km, literally lighter than a feather, proportionally speaking, it would be unlikely to do much, if any, physical damage. In the worst-case scenario, where the cable is severed near the top, in space, the released counterweight would fly out of Earth orbit and nearly the entire ribbon would begin to fall down and wrap around the planet. As the ribbon fell it would gain velocity, and any ribbon above the first 1000 km would burn up when it hit the atmosphere, producing long, light ribbons that are meters to kilometers in length. It would be a mess and a financial loss, and probably an impressive light show in the upper atmosphere, but nothing like a planetary disaster. Some toxicity issues are being investigated in connection with inhalation of ribbon debris, but initial results indicate that the health risks would be small.

Five years ago, most of the space community considered the space elevator a far-future proposition at best. With the advent of carbon-nanotube composites and the conclusions of recent studies, the space elevator concept is moving toward mainstream acceptance. The current ribbon design has attracted considerable interest from NASA headquarters, the European Space Agency, and the U.S. Air Force. Independent evaluations by NASA and ESA are under way, and it is my belief that their findings will add substantial credibility to the program.

80 000 km — 90 000 km — 100 000 km

To avoid problems with cable oscillations induced by tidal forces, my ribbon design calls for a natural resonant period—7.2 hours—that does not resonate with the 24-hour periods of the moon and sun. Any oscillations that do occur would be damped by the mobile anchor station.

Induced electrical currents would be generated only if the ribbon cut through Earth's, or an interplanetary, magnetic field. Because the ribbon would be stationary relative to Earth's magnetic field, only dynamic changes in the magnetic field could cause currents in the ribbon, and these would be small. The interplanetary magnetic field is also small, except in cases of extreme solar activity, and even then, the currents generated would be on the order of milliwatts and easily dissipated. Currents caused by charged plasma in Earth's ionosphere would also be negligible, because the ribbon's composite material would have high electrical resistance.

THE LAST CHALLENGE, and the one that sparks the most interest in today's geopolitical climate, is terrorism. Despite the elevator anchor's remoteness and defensibility, an attack that severs the elevator cable—for example, by detonating a bomb planted on an elevator car—is a possibility. So what would happen if the cable were cut?

Science-fiction scenarios have portrayed a space-elevator cable failure as a global disaster, but the reality, for my design, would be nothing of the sort. Remember that the ribbon's center of gravity is in geostationary orbit, and the entire cable is under tension as the counterweight swings around Earth. If the ribbon were to be severed near the bottom, all the cable above the cut would float up and start to drift. Calculations show that the ribbon and counterweight would most likely be thrown out of Earth orbit into open space.

If the initial estimates are confirmed and a space elevator is constructed, it will open space for applications we can barely imagine. With a space elevator providing cheap, easy, low-risk access to space, people's lives on Earth could be immeasurably enhanced as the wealth of the solar system is brought to their door.

Humanity would at last be poised to make its next move into space and onto the moon and Mars—not as a horribly inefficient, one-shot deal but as a continuing enterprise. Space travel would become part of our everyday culture. Just as the development of stone tools opened up huge new habitats and ways of life to our distant ancestors, so, too, will the space elevator transform humanity's destiny. ■

ABOUT THE AUTHOR

Bradley Carl Edwards spent 11 years on the staff of the Los Alamos National Laboratory, leading advanced technology efforts for lunar missions and a Europa orbiter mission. Since leaving Los Alamos, Edwards has led development of the space elevator, organizing conferences and conducting research. He is the founder and president of Carbon Designs Inc., in Dallas, which is developing high-strength materials for a range of applications, from aerospace structures to sports and recreational products.

TO PROBE FURTHER

For more information about the space elevator project, visit http://www.spaceelevator.com.