

Stairway to the heavens

Escaping the Earth's gravitational clutches by climbing up a long rope made from carbon nanotubes is a pretty madcap idea. But, as **David Appell** found out from a recent "space elevator" conference, there are plenty of enthusiasts out there who are determined to make the concept work

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Imagine beings that live at the bottom of a deep well. Looking up, they glimpse a few stars, while instruments that they have sent above reveal a vast, enticing macrocosm. A few have ridden thundering missiles out of the well, but only for short times and at great risk and expense to themselves. They are seemingly trapped, waiting for a destiny that never arrives.

Those beings, of course, are us, and the well is made from gravity. But getting out may be as straightforward as riding an elevator, if only there were a way to build it. Unlikely though it sounds, that may one day be possible.

Building a space elevator is almost within our capability, a few scientists and engineers are now saying. And with it, our access to space – for putting satellites into orbit, heading out into the solar system or using it as a new tourist destination – could suddenly become cheap and safe. Elevator enthusiasts have the basic physics all worked out, they think they know the pitfalls and the solutions, and they have narrowed their quest to building the elevator from a material that has already been discovered. They are dreamers, for sure, but humans once imagined things that seemed equally impossible, be it a railway that crosses continents or a globally linked network of calculating machines with a terminal in every home.

The space-elevator concept

The problem, in more detail, is this: it takes at least 62 megajoules of energy per kilogram to escape the Earth's gravity well. At standard rates for electricity, this is equivalent to just \$3, yet NASA spends more than \$10 000 to get a kilogram of payload into low Earth orbit – to altitudes of 200–2000 km – and the ride both ways is hairy and sometimes deadly. Indeed, up to 95% of a rocket's mass goes on its propellant and we are probably nearing the limits of chemical rocket technology.

The idea of a space elevator is to build a tower that stretches beyond geosynchronous orbit (GEO), which lies 35 800 km above sea level, and is anchored in place by centrifugal force. Robotic "climbers" would be able to ride up and down the tower, cheaply and safely. In essence, it would be a railway to a station that serves up the whole solar system, taking anyone and anything where few humans have ever gone before.

But here's the rub: a free-standing tower would realistically need to be 100 000 km long, and it would have to be able to support its own huge weight. This calls for an ultrastrong, ultralight material, and for decades after the space elevator was first conceived no known material had the required strength-to-density ratio that could do the job.

Then, in 1991, carbon nanotubes were discovered.

From fiction to physics

The space elevator was first dreamed up by the eccentric Russian rocket scientist Konstantin Tsiolkovsky in 1895. Made deaf from scarlet fever at the age of 10, he was not allowed to attend school and was entirely self-taught. But Tsiolkovsky had a wild imagination and a genius for space aeronautics, and was inspired to ask how high the newly built Eiffel Tower might have gone. As far as his vision is concerned, the world has still to catch him up.

Two engineers with strong interests in space, Yuri Artsutanov and Jerome Pearson, were the first to (independently) put some solid physics behind the idea of a space elevator, in 1960 and 1975, respectively. A tower that extended only to GEO would buckle under its own weight, unless it was hundreds of kilometres in diameter. So they both rediscovered what Tsiolkovsky had known: the best way to balance the tower is to extend it from Earth's surface to GEO and then *beyond*. The portion of the tower below GEO has a net force towards the Earth, while that above GEO a net outward force on it, so the entire tower would be under tension, balanced about the GEO point. Just attach the bottom to the planet, and Bob's your uncle.

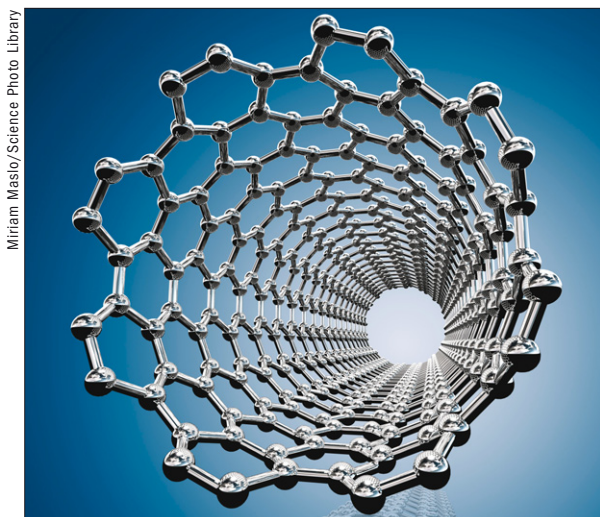
But Bob is also a prankster. Both researchers elegantly derived an equation for the tower shape that minimizes its weight. Although the total weight is an integral that can only be solved numerically, Artsutanov and Pearson concluded that the elevator should be tapered exponentially, thickest at GEO and thinnest at the ground and top. In addition to depending on the mass, radius and rate of rotation of the planet to which it is attached, the actual size of the tower also depends on the strength-to-density ratio of the material from which it is made.

At a Glance: Space elevators

- First devised in 1895 by eccentric Russian rocket scientist Konstantin Tsiolkovsky, the main feature of a space elevator would be a lightweight and super-strong tether extending from the Earth's surface to geostationary orbit and beyond
- "Climbers" could ride up and down the tether, which would be counterbalanced by a large mass at its end-point
- Space elevators were little more than fantasy until strong yet light enough materials in the form of carbon nanotubes were discovered in 1991
- If built, an elevator could be a cheap and easy route into orbit – and even allow astronauts to catch a waiting spaceship to take them on to other destinations in the solar system
- Several private firms have been set up to promote and research space elevators, while NASA is running two competitions designed to encourage the concept



The Space Elevator Visualization Group



Miriam Maslo/Science Photo Library

Wonder material Carbon nanotubes could make a real space elevator.

It is simplest to think of the tower material in terms of its “characteristic” or “breaking” length, which indicates how much of its own weight the material can hold up before it breaks. For a uniform material with a constant cross-section, this length is simply the strength-to-density ratio divided by the acceleration due to gravity, g . Steel wire has a characteristic length of about 54 km, which seems impressive but, according to the taper equation, would require a tower that is 10 000 trillion trillion trillion (10^{40}) times larger in cross-sectional area at GEO than at the Earth’s surface (see box on p33). Even a tower made from Kevlar – the lightweight body-armour material that is as strong as steel but only a fifth as dense – would be 250 million times broader at GEO than at its thinnest points.

So when Arthur C Clarke wrote his 1979 novel *The Fountains of Paradise*, the orbital tower that is at the book’s heart had to be made from a fictional hyperfilament akin to diamond in order to have enough strength but not too much mass. Clarke’s tower was more like an enclosed railway tunnel and could never be built – but the book (for which Clarke had consulted Pearson himself) brought the idea of a space elevator out of obscure journals and helped to inspire a new generation of space-elevator enthusiasts.

In the early 1990s those enthusiasts included Boris Yakobson, who was then at North Carolina State University, and the late Richard Smalley from Rice University who shared the 1996 Nobel Prize for Chemistry for helping to discover buckyballs – a new form of carbon in which 60 atoms are arranged into a hollow sphere. Doing computer simulations on carbon nanotubes – a cylindrical, chicken-wire-like hexagonal mesh of carbon atoms derived by stretching a buckyball – Yakobson and colleagues quickly found that these materials are extremely strong. A mere 1 mm thread could hold up a mass of 20 tonnes. Upon hearing the results, Smalley phoned Yakobson to say that the long-sought material for a space elevator had arrived.

Return of the elevator

The discovery of carbon nanotubes breathed new life into the space-elevator idea, moving it from science fiction to high-level engineering studies. Being only 30%

denser than water, and 32 times stronger than steel, carbon nanotubes have a theoretical breaking length of more than 10 000 km. Built from them, a tower’s ratio of GEO to base area need be only 1.6. The broader world’s excitement about the many remarkable properties of these new materials only added to the potential of the space elevator.

Carbon nanotubes are microscopic: a pile of them looks like fine, black soot. The tensile strength of an individual tube with a single cylindrical wall has been measured as high as 120 GPa (1.2×10^{11} Pa) but in theory it could be up to 300 GPa. Bradley Edwards, a former Los Alamos physicist who has started several elevator-related companies in recent years and who carried out a detailed study of how to build and operate a space elevator for NASA’s Institute for Advanced Concepts in 2001–2003, thinks that about 130 GPa would be needed for a safe orbital tether.

But how could you make a 100 000 km-long structure from carbon nanotubes? Unfortunately, no-one knows, or at least not yet. Although the longest such tube made to date is 55 cm in length and just a nanometre wide – created by Weizhong Qian and colleagues at Tsinghua University in Beijing – their growth is difficult to control. However, no-one envisions an elevator made from a single carbon nanotube, which would be too fragile on its own. Instead, individual tubes would probably be woven or braided together, thermally annealed and embedded in a composite.

Speaking at a space-elevator conference in August, Mark Haase, a chemical-engineering PhD student at the University of Cincinnati, discussed how to select and bundle carbon-nanotube threads, weaving a kind of rope with up to a trillion nanotubes per square centimetre. Attended by about 65 elevator enthusiasts, academics and even a few entrepreneurs, the conference is an annual event held at Microsoft’s headquarters in Redmond, Washington. The key, Haase believes, and also the bottleneck, is maximizing the intramolecular forces that bind nanotubes along their long dimension, which are a balance between short-range, repulsive forces arising from the quantum-mechanical Pauli exclusion principle and longer-range, attractive Van der Waals electrical forces.

Many factors remain to be perfected in order to make stronger, more durable nanotube materials. Defects along the tubes – be they from impurities, dopants or the occasional pentagon or heptagon where a six-sided hexagon would ordinarily be – can reduce attractive forces. Radiation from solar storms or cosmic rays could also induce serious tether-damaging defects, which is why the nanotubes would ideally be self-healing. Another problem is that the tether could be weakened if made from tubes with a non-uniform diameter. Indeed, Haase believes a key to making better spinnable nanotube arrays is finding a catalyst that slows down the tendency of metal particle clusters to attach themselves to nanotubes during synthesis – an unwanted effect that stops them growing any further. (Known as “Ostwald ripening”, this process also explains why partially thawed ice cream becomes crunchy after refreezing.)

But Haase is optimistic about the use of nanotubes in space elevators, telling delegates in Redmond that “we

No-one envisions an elevator made from a single carbon nanotube, but individual tubes would be braided together and embedded in a composite

Elevators by numbers

A practical space elevator that allows astronauts to reach geostationary orbit would have to be tethered to the ground but extend a hundred thousand kilometres into space to stop it from buckling under its own weight. Working independently, engineers Yuri Artsutanov and Jerome Pearson derived an equation in 1960 and 1975 that showed that such an elevator also has to be tapered, being thickest at geostationary orbit and thinnest at the ground and at its furthest point in space.

They calculated that the ratio of the tower's cross-sectional area at its thickest and thinnest points is $\exp(fR/h)$, where R is the radius of the planet, h is the "breaking length" of the tower material and f is a number that depends on the planet's mass, radius and rate of rotation, being 0.776 for Earth and 0.753 for Mars. In fact, $f = 1 + R^3/2S^3 - 3R/2S$, where S is the radius of geosynchronous orbit and $S^3 = GM/\omega^2$, where G is the gravitational constant, M is the mass of the planet and ω is its rate of rotation. Using steel wire, where h is 54 km, the tower's cross-sectional area would have to be 10^{40} times larger at its thickest point than its thinnest point. A tether made from carbon nanotubes ($h = 10\,200$ km) would have a ratio of just 1.6.

have unsolved, not unknown problems", and adding that the problems are all "fairly approachable". However, Haase's PhD supervisor Vesselin Shanov – who co-directs Cincinnati's Smart Materials Nanotechnology Laboratory and helped to found General Nano, the largest carbon-nanotube manufacturer in the US – is more cautious. "We're far away from making a space elevator," he argues, estimating that it will be another 50 years before one is built. "Spinning is a very tricky process," he adds, pointing out that although General Nano can currently make braids that are $28\mu\text{m}$ thick and contain about 3000 nanotubes in cross-section, this is still far from what is needed for a space elevator.

Toilets on the space train

A working space elevator may well be surprisingly slight. Edwards, whose 2002 book *The Space Elevator* provides a framework for many in the elevator community, proposes a "ribbon" made from a nanotube composite of many individual fibres, each with a tensile strength of about 100 GPa. In appearance, the elevator might seem like little more than flypaper. Just microns thick and only 10 cm across at the base, at low-Earth orbit and beyond it would be barely more than a metre wide.

"Climbers", weighing perhaps 20 tonnes, would ferry people and equipment up and down at speeds of about 200 km h^{-1} , gripping the ribbon between pinched rollers, its motors powered by megawatt lasers beamed up to panels of photovoltaic cells. Reaching GEO to gawp at the unprecedented view would take about a week, while a journey beyond that point would involve having to brake to overcome the net outward force. Once there, a waiting spaceship could then transport travellers into the solar system, taking you to the Moon, Mars or (with rocket assistance) to Jupiter and beyond.

Elevator enthusiasts envisage locating the ribbon's base on a floating platform near the equator in the eastern Pacific Ocean. That location would minimize lateral forces on the tether caused by the Earth's rotation



The Spaceward Foundation

The real thing

The Spaceward Foundation and NASA run the Power Beaming Challenge to find a space-elevator climber. (Pictured: the 2007 KCSP entry being tested in Utah.)

and also reduce problems from tropical storms (which never cross the equator), lightning and large waves. Anchoring it at sea in this way would also allow the ribbon to be moved to avoid dangerous space debris at low Earth orbit, while, should the tether break or be severed, any big strands or climbers plummeting to the Earth would be unlikely to hit anybody.

To keep the ribbon in balance about GEO, it would need to extend 144 000 km above the Earth's surface. However, the ribbon could be made shorter by attaching a counterweight to its top end, the mass of which would depend on the length, shape and composition of the ribbon. Padmanabhan Aravind, a physicist at Worcester Polytechnic Institute in the US, has calculated that a 100 000 km carbon-nanotube ribbon would have a mass of about 98 000 kg – assuming 1000 kg climbers, a constant tensile strength of 100 GPa and a safety factor of 2 for the ribbon stress – while the counterweight would be 53 000 kg, with a ratio of GEO to base area of 4.28. The counterweight could be made of anything – rocks, assorted space junk or even the initial climbers that would build up the tether in stages.

Besides the need to develop a suitable tether material, any real space elevator would also need to overcome countless other problems and pitfalls – from the capriciousness of the Earth's weather to dealing with space debris, micrometeors, solar storms and cosmic rays. Oscillations and electric currents could be induced in the ribbon, which could be eaten by sulphuric acid in the upper atmosphere. How would a damaged ribbon be mended? Where would the laser power come from? And who would have controlling legal authority over the tether?

As for what a space elevator might cost, numbers such as \$6–20bn are bandied around, but actually no-one knows for sure. Ben Shelef, an aeronautical engineer and co-founder and chief executive of the elevator-promoting Spaceward Foundation, says simply that "it's not realistic at this point" to attach a price tag to any space-elevator design. But researchers in the field are confident that answers will come. Indeed, one paper presented at the session on "space elevators and tethers" at last year's International Astronautical Congress in Prague even went so far as discussing "preliminary systems requirements for the space toilet on the space train". Others are also dreaming of space elevators on the Moon and Mars (see box on p34).

Eccentric ideas

If building a space elevator is doable, albeit pretty far-fetched, could a similar tether take us from the Earth to the Moon? Sadly, the short answer is “no”. Apart from being extremely expensive (the tether would have to be almost 400 000 km long), the bigger problem is that the Moon is not a constant distance from the Earth but travels in an ellipse, with the Earth–Moon distance varying by almost 43 000 km over the course of one lunar orbit (27.3 days). Therefore a space elevator that connected the two would somehow have to be stretchable or retractable or else it would break apart.

However, Jerome Pearson, whose 1975 paper helped spawn renewed enthusiasm for the space-elevator concept, favours first building a lunar space elevator. It would extend from the Moon’s surface to the first “Lagrange point” (L1) in the Earth–Moon system (about 58 000 km from the centre of the Moon, where the centrifugal force is the net gravitational pull) and beyond to a counterweight about 100 000 km from the Moon. In the Moon’s weaker gravity, Pearson believes that an elevator made from a ribbon of M5 – an existing super-strong



Obstacles to overcome A space elevator on Mars would have to avoid run-ins with its moon Phobos.

commercial synthetic material with a breaking length projected to be as high as 570 km – would need only be 30 mm wide and 23 μm thick, roughly similar to aluminium foil.

The disadvantage is that climbers on the lunar elevator must be light, carrying payloads but no people and taking three weeks or more to reach a station at L1. But not everyone in the elevator community is as enthused about starting with a

lunar elevator, even as a learning opportunity. “I see it as a very large distraction,” says Ben Shelef of the Spaceward Foundation. “And I don’t see the point. All the things that are difficult here are not there. It’s like going to the Moon before you go to Mars – it doesn’t teach you much about what you need to solve.”

As for building a “standard” space elevator on Mars, it would be shorter than the equivalent device on Earth because its stationary orbit is only about half as far out. However, the situation is complicated by Mars’ moon Phobos, which is small but very close to the planet’s surface, intersecting the equatorial plane once every five hours. Indeed, in his book *Red Mars*, the US sci-fi writer Kim Stanley Robinson envisages using a captured asteroid as the counterweight for a Martian space elevator. His Martian elevator is 10 m wide at the base, making it a huge and heavy thing, possibly because the novel was published in 1992, barely a year after carbon nanotubes were discovered. Midway through the book the elevator is sabotaged by terrorists and crashes to the surface, wrapping once around the planet and then some.

People, progress and plans

Despite the practical difficulties involved in a space elevator, signs of interest in the concept abound. Conferences are appearing more frequently around the globe, and in addition to the Spaceward Foundation there are at least three other organizations promoting the idea: EuroSpaceward, the Japan Space Elevator Association (JSEA) and an umbrella group known as the International Space Elevator Consortium. Shuichi Ohno, chairman of JSEA, believes the idea appeals to a generation raised on sci-fi animation and films about spaceships and distant colonies. “Many people think that humans must go to space in the near future as part of our nature,” he says.

Although space elevators do not appear on NASA’s Space Technology Roadmap, the agency has committed big money to two competitions that are designed to encourage the concept. In 2009, as part of NASA’s Power Beaming Challenge, it awarded \$900 000 to a Seattle-based company called LaserMotive for moving a 5 kg robotic climber up a 1 km cable suspended beneath a helicopter in the Mojave desert using a laser beam that drove an electric motor via solar cells, with the climber completing the job in just over four minutes.

NASA also runs the Space Tether Challenge, which is offering \$2m to the first group to build a material that provides 5 “megaYuris” of tension strength, where 1 megaYuri is a unit invented by elevator buffs in honour of elevator pioneer Yuri Artsutanov and equals 1 GPa per unit density (measured in grams per cubic centimetre). The prize, however, remains unclaimed, being without a winner five years after it was launched. Similar (though less lucrative) competitions have been held in Japan and Europe that focused on small traction-based climbers.

The private sector has also got in on the act, with several companies having been set up trying to find a business model that can exploit the elevator concept (some of which have already folded). These include Highlife Systems, Carbon Designs, Liftport, Blackline Ascension and Odysseus Technologies; while defence giant Lockheed Martin even has a US patent (number 6491258) on a specific version of a space elevator. Patents are also held by other firms covering particular elevator implementations.

The space elevator is enticing because its scientific sweetness allows physicists and engineers to play with it, but it is far enough away that pesky details can always be put off until later. “If you have built castles in the air, your work need not be lost,” wrote the early US environmentalist and dreamer Henry David Thoreau in his classic 1854 book *Walden*. “That is where they should be. Now put the foundations under them.” Or, as one might say today, a very long tether to the future. ■

More about: Space elevators

P K Aravind 2006 The physics of the space elevator *Am. J. Phys.* **75** 125

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P Ragan and B C Edwards 2006 *Leaving the Planet by Space Elevator* (lulu.com)

The Space Elevator Consortium (www.isec.org)