International opportunities and technical challenges for the space elevator

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Executive Summary: The space elevator is a hypothetical concept for placing satellites in orbit around Earth that would result in dramatic cost savings over traditional rocket launches. The space elevator would work by placing a counterweight in space that is tethered to the Earth's surface and held in place by the centrifugal force of the Earth's rotation. Technical challenges, particularly those related to the tether material, have prevented a space elevator from getting past the design stage. Should future advances in materials science allow the space elevator to be built, consideration should be paid to the geopolitical influence that a real space elevator might have. Its unique combination of cost, wartime utility, and vulnerability mean that a peaceful consortium of nations working together should be considered as a potential management model.

I. Introduction

Spaceflight remains expensive today due to an unavoidable physics problem: rockets must carry their own fuel in addition to their payload (i.e., passengers and cargo). Each additional kilogram of payload requires extra fuel, requiring most of a rocket's weight to be attributed to fuel storage as opposed to payload. For a simple, single-stage rocket that aims to launch a satellite into low-Earth orbit, fuel alone can easily account for more than 95% of the rocket's weight (Pettit 2012). This, in turn, drives launch costs to be more than $1,000 per kilogram of payload (Barry and Alfaro 2022).

Space elevators aim to change this dynamic by removing the need to carry fuel alongside the payload. A space elevator is a proposed megastructure composed of a counterweight in space attached via a tether to the Earth's surface (Aravind 2007). The counterweight is positioned far enough from the Earth's surface that the tether is kept in tension by the rotation of the Earth, in much the same way that an Olympic athlete might perform the hammer throw (Figure 1). A passenger wishing to go into space, instead of riding in a rocket, can simply enter a "climber" (a vehicle that attaches to the tether and climbs up it) to ride up to the altitude desired. At the altitude of geosynchronous orbit (where the orbital period is equal to one day – about 35,786 kilometers above the surface), the passenger can simply detach from the tether and immediately be in orbit around the Earth. If the passenger climbs just past geosynchronous altitude, they can slide along the tether and be flung out to other planets, or even beyond the Solar System.

Although space elevators have a long history in both physics and the public imagination, none have ever been built. This technology assessment examines: (1) a brief history of space elevators; (2) the opportunities that space elevators present; (3) some of the challenges associated with building a space elevator and why they remain out of reach for the foreseeable future; and (4) the policy implications of a space elevator, were one ever to be built.

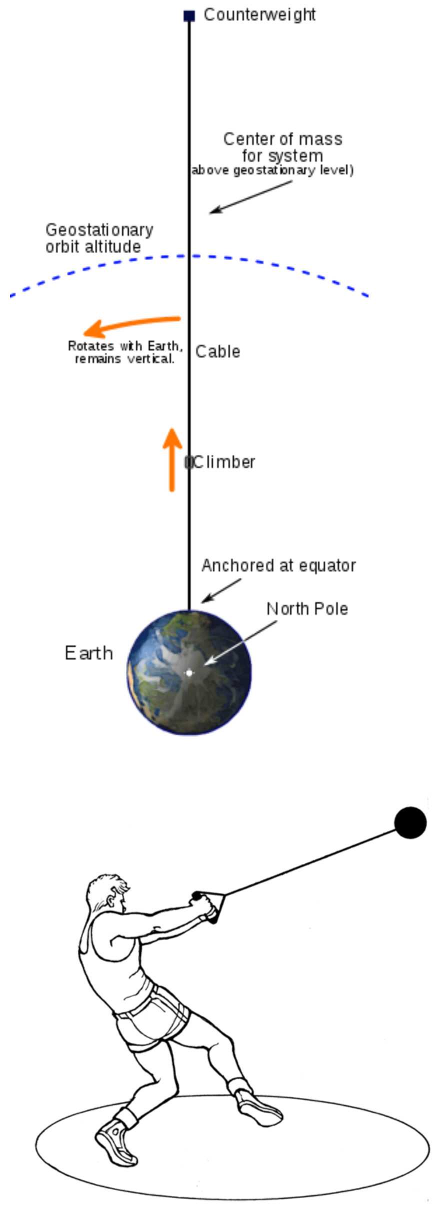

Figure 1*: The space elevator (left) operates on much the same principle as the hammer throw (right). A counterweight is placed in space and attached to the earth via a tether, which is held in tension by the rotation of the Earth. The dynamics of the space elevator are somewhat more complicated than the hammer thrower because the strength of Earth's gravity weakens appreciably at great distances, but the general idea is the same. In some space elevator designs, the cable is itself in orbit around the Earth and does not need to be physically tethered to the ground. Source: Pearson Scott Foresman, Public domain, via Wikimedia Commons; Skyway and User: Booyabazooka, CC BY-SA 1.0 via Wikimedia Commons.*

We focus specifically on the geopolitical implications, suggesting that a consortium of nations with common ownership of the space elevator, in the model of the International Space Station, would be the most attractive way forward. In particular, we describe why Japan and the United States are the two countries best-positioned to begin such a consortium.

i. A brief history of the Space Elevator

The first concept of a space elevator, in which a tower could be climbed to reach geosynchronous orbit, originated in the late 19th century with the Russian physicist Konstantin Tsiolkovsky, who imagined a compression tower in the image of the Eiffel Tower in Paris (Price 2000). Tsiolkovsky's vision was impractical because no material is known to be strong enough to support the enormous weight of such a structure, and the idea sat idle for decades.

The modern form of space elevators emerged in the 1970s after Jerome Pearson, a researcher working at the U.S. Air Force Research Laboratory, published an analysis (Pearson 1975) of a space elevator composed of a cable held in tension, not compression. Pearson's analysis showed that a tapered design – where the cross-section of the cable is widest at geosynchronous orbit and tapers exponentially to the anchor point on Earth and to the counterweight in space – was the most practical and least costly design. He also derived requirements for the cable material, finding that metals like steel and titanium were too heavy to be practical, but that certain forms of carbon could theoretically be strong and lightweight enough.

As the idea began to take hold throughout the late twentieth century (bolstered by depictions of space elevators in works of science fiction like The Fountains of Paradise by Arthur C. Clarke), space elevators eventually began to catch the attention of the mainstream scientific community. In the late 1990s, the U.S. National Aeronautics and Space Administration (NASA), as part of an initiative to study novel technologies, funded several articles in academic journals by Bradley Edwards of Los Alamos National Laboratory that describe in detail some of the design considerations that would come to bear on the construction of a real space elevator (Edwards 2000; 2002; 2003).

Edwards was, and remains (Gibson 2022), optimistic that a space elevator could be built using today's technology, but that perspective is not unanimous in the scientific community (Pugno 2007). Currently, the best candidates for a tether material are generally either too heavy to be practical (this category includes composites like Kevlar) or can only be manufactured in small quantities (such as carbon nanotubes and graphene). For this reason, most current research on space elevators assumes that a breakthrough in materials science will be needed before efforts to build one can begin in earnest.

ii. Scientific and economic opportunities provided by the space elevator

The primary benefit of a space elevator is the dramatically lowered cost of launching a payload into orbit. Most of these cost savings come from the reduced fuel requirements: the payload no longer must carry its own fuel, so all available power can go directly towards putting the payload into orbit. Space elevators are themselves still costly; after all, the payload still requires significant amounts of energy to reach orbital speeds and must be carried by specialized climbers, not to mention the cost of constructing and launching the tether itself. Even the most optimistic estimates for the cost of constructing a space elevator run to the tune of tens of billions of dollars (Barry and Alfaro 2022). Because rocket launches into geosynchronous orbit cost about $5,000 per kilogram, however, the potential savings are dramatic. Direct cost comparisons between conventional rockets and the space elevator are complicated because of the different operational models: rockets incur costs each time they are launched, while the space elevator requires a substantial up-front investment followed by reduced expenses per launch (Barry and Alfaro 2022). The space elevator is also best-suited to launching payloads into geosynchronous orbit – reaching low-Earth orbit from there requires a rocket to perform an orbital maneuver. Still, the best modeling estimates place the cost per kilogram of payload to be around 2.5% that of an equivalent rocket launch (Swan et al. 2013).

A space elevator would also be more reliable and safer than a rocket launch. Without thousands of kilograms of explosive fuel, there is reduced danger of a catastrophic failure upon launch. If the climber encounters a mechanical problem, it can be designed to 'fail-safe' and clamp on to the tether until a rescue climber is able to reach it. The space elevator would also be unfazed by mild weather events – Pearson found that even tornado-force winds would not cause undue stress to the tether (Pearson 1975) – meaning launches could take place on schedule more reliably than rocket launches. And without the intense vibration, acceleration, and space constraints associated with a rocket launch, satellites could be built to more relaxed engineering standards, further reducing costs.

Cost savings are even bigger for launches beyond geosynchronous orbit, because the climber does not need to be powered beyond that point – energy is extracted for free directly from the Earth's rotation. It therefore would require the same amount of energy to launch a satellite into geosynchronous orbit as it would to launch it to Jupiter (Peet 2021). Opening the deep space industry for pennies on the dollar will likely have tremendous implications for science and exploration: scientific probes could carry more complicated instruments (and therefore return better data), more missions could be launched each year, expanding opportunities for promising but risky experiments, and economically nonviable proposals, such as asteroid mining, could suddenly become profitable.

In addition to their low cost, deep space missions with a space elevator would be just as fast as conventional rocket launches: trips to Mars could be completed in as little as one month, Jupiter could be reached in one year, and it would only take three years to reach Uranus (Peet 2021). These travel times compare favorably to projected transit times using a conventional rocket launch (150 days, 0.9-1.2 years, and 3.8-4.7 years, respectively) (Zangari et al. 2019; Mohanalingam and Carr 2023).

Another benefit of the space elevator is environmental: rocket launches often burn significant amounts of polluting fuel (Piesing 2022), while also contributing to noise pollution. In fact, large rocket launches have sophisticated water suppression systems specifically designed to limit the acoustical damage to launch infrastructure (Boen 2015). The space elevator could be operated entirely with environmentally friendly power sources, with silent operation. Environmental analyses that compare conventional rocket launches to the space elevator are difficult to perform on an "apples-to-apples" basis, in part because of the unknowns of the manufacturing process needed for the tether material. Still, assuming that the tether is made in a similar manner to CNTs today, the life-cycle environmental cost of the space elevator across factors including global warming potential and chemical waste is reduced compared to an equivalent number of rockets (Harris, Eranki, and Landis 2019).

iii. Technical challenges

The single greatest technical challenge to constructing a space elevator is finding a suitable tether material. In theory, any strong material, such as steel or aramid fibers (brand name Kevlar), would work: Pearson's original analysis found that the weaker the material, the thicker the cable would have to be at geosynchronous altitude, but (perhaps surprisingly) there are no minimum strength requirements for the material. However, the taper ratio (the ratio of the cable cross-section at geosynchronous altitude to the cross section at Earth's surface) for all but the strongest and lightest materials is impractically large; even for Kevlar, it is 106, requiring billions of tons of Kevlar to be launched into orbit (Popescu and Sun 2018). Instead, focus has shifted onto carbon nanotubes, which have a theoretical strength (Pugno 2007) that is more than sufficient to build a tether with a moderate taper ratio. Real samples produced in today's laboratories are not quite this strong due in part to material imperfections and are not yet large enough to be sufficiently useful – the largest samples to date appear to have stalled at around 0.5 meters in length (Pugno 2013; Zhang et al. 2013).

A real space elevator tether would likely not use nanotubes that are thousands of kilometers long – imperfections are very difficult to prevent as the tubes grow longer and are exposed to micrometeoroids, radiation, and corrosive elements in the upper atmosphere (Edwards 2000). Instead, a realistic tether would likely be composed of macroscopic lengths of carbon nanotubes in segments, attached to one another by a composite material. The composite, of course, is not as lightweight as the nanotubes, so determining the right ratio of segment length to taper width while maintaining sufficient safety margins is a future engineering challenge. Other additions, such as anticorrosion coatings, will also add to the weight of the tether.

The tether is expected to experience failures, as it is impacted by micrometeoroids in space, random nanotube breaks, and chemical deterioration. It is therefore a good idea to incorporate a self-repair mechanism, likely using robots, to attach new carbon nanotubes to segments with broken filaments. It turns out that using repair robots could reduce the needed safety margin, which would more than make up for the added weight of repair robots (Popescu and Sun 2018). Still, designing and building robots that can detect tether failures and fix them automatically will be quite difficult. How will the robots detect filament failures? What composite can they use to attach new filaments without adding excess weight to the tether? How can they avoid interrupting the journey of other climbers that carry payloads? These challenges may not be insurmountable, but they will require significant research to solve.

While the tether is under enough tension to be unaffected by even the harshest winds, some extreme weather events could still pose a risk to the space elevator, and it is prudent to keep the space elevator away from bad weather. Large storms can carry debris at high speed, which risk cutting (if not snapping) the tether. Lightning poses another risk: a direct lightning strike on the tether could very possibly destroy it. The location of the space elevator should therefore be chosen to minimize the number of expected lightning strikes, and further research may be needed on how to mitigate the effects of lightning (Edwards 2000). One option is to anchor the space elevators to a seafaring platform, much like a floating oil rig, that can be maneuvered away from tropical cyclones and other hazardous storms. Above the atmosphere, micrometeoroids pose the biggest risk to the space elevator. Because they move at high speed, micrometeoroids could easily tear a hole in the tether that would cause it to snap. Mitigation measures could include radar to track larger pieces of debris (and maneuver out of the way) along with robust self-repair mechanisms, and a strong safety margin.

In the unfortunate event of tether break, some care would need to be taken to prevent further harm. Any assets located at geosynchronous orbit or climbing along the tether would need to detach from the tether, the upper portion of which will be flung out into space. As the lower portion falls to the Earth, it will pick up great speed due to the lack of air resistance above the atmosphere, while portions in the atmosphere will be slowed down by air resistance. Computer modeling of this complex dynamic suggests that areas East of the anchor point may be in danger from high-speed tether impacts (Aslanov et al. 2013). A self-destruct capability that breaks the tether into smaller, more manageable lengths could therefore be considered to prevent pieces of the tether from striking the ground at high speed.

Most of the technical challenges outlined here appear to be solvable with sufficient engineering work. Identifying a suitable tether material, on the other hand, presents a major challenge that likely cannot be overcome without sustained progress in research on carbon nanotubes and graphene. Given the uncertainties on how this research will progress, researchers have proposed several alternative space elevator designs that circumvent the tether material requirements, which are outlined in the next section.

iii. Technical challenges

The strength requirements for the tether material are derived directly from the strength of Earth's gravitational field. Naturally, a weaker gravitational field would impose weaker requirements on the tether material. Indeed, it is conceivable that a space elevator could be built on the far side of the moon using existing materials, though this would not solve the problem of getting payloads from the Earth to the moon site. One approach to reaching the moon is the Spaceline, a cable tethered to the surface of the moon and hanging towards the Earth, passing through the L2 Lagrange point. Built using conventional materials (such as aramid fibers), the Spaceline could be used to lower the cost of transporting materials to the moon: a rocket is needed only to reach the lower end of the cable, at which point climbers can then carry the payload the remaining distance to the surface of the moon. It is estimated that the Spaceline could reduce the costs of delivering payloads to the moon by as much as 67%, although construction would itself be quite costly (Penoyre and Sandford 2019).

Another possible alternative is the Skyhook: an orbiting cable held in tension by two rotating counterweights. The period of rotation of the counterweights is set to exactly counter the speed of the Skyhook orbit, such that when each counterweight reaches its lowest altitude, it is stationary relative to the Earth's surface[1]; the path of each counterweight forms a cycloid around the Earth. As the counterweight touches down at or near the Earth's surface, payloads can simply be attached, and are smoothly accelerated up into orbit, where they can be released. Although the Skyhook idea is well-founded and buildable with today's materials – a NIAC-commissioned study concluded they were feasible 20 years ago (Bogar 2000) – they suffer from one crucial disadvantage compared to the space elevator: the launch of a payload into orbit saps energy away from the Skyhook itself. The Skyhook therefore has a finite usable life unless orbiting payloads are caught by the counterweights and then lowered to Earth at the same rate they are launched, which seems unlikely. We therefore focus on the traditional space elevator for the rest of this perspective.

II. International political challenges to space elevator development

Space elevators would be high-priority targets in wartime due to their fragility and military advantage in launching satellites. Military defense and international cooperation are two approaches for dealing with potential military conflicts, each with distinct costs and benefits.

A defensive strategy would place anti-aircraft and other defensive weapons near the space elevator tether point to defend the site against any kinetic attacks. Because the space elevator is fragile, large, and expensive, the cost ratio[2] of attacking the space elevator is quite favorable for the aggressor. A large investment of weapons would likely be needed to defend the space elevator (and the associated power-beaming stations), which would be highly vulnerable to anti-satellite missiles and long-range cruise missiles. Unconventional attacks involving

[1] If the Skyhook reaches down all the way to the ground, attaching payloads is straightforward, but air resistance will sap energy from the Skyhook. Conversely, the Skyhook could dip down only into the upper reaches of the atmosphere to avoid air resistance but delivering payload would require a rocket or other high-altitude vehicle.

[2] In this instance, cost ratio refers to the ratio of the cost of destroying the elevator to the cost of constructing it.

drones or directed energy weapons could also be effective and cheap, although more detailed analysis of these weapons is required to compare them directly to conventional weapons. Due to the dynamics of tether rupture described above, an adversary seeking to destroy the space elevator would only need to successfully create a single break in the tether to destroy the elevator. The defender would therefore be obligated to overmatch their adversary's capabilities, meaning that any defensive strategy is likely to be costly and difficult.

With complete control over the space elevator, the host country would nevertheless have a powerful advantage in space warfare. An "arms race" could therefore develop in which each country seeks to build its own space elevator (along with the necessary defensive capabilities) whose access could not be revoked during wartime.

An alternative strategy for avoiding military conflict over space elevators is to remove the incentive to destroy the elevator in the first place. By building the elevator in collaboration with other nations – even adversarial ones – and sharing its use, each country would be disincentivized from destroying it. This collaborative spirit could be strengthened further by restricting space elevator use only for commercial and scientific payloads. Under this model, all partner nations would agree to allow other nations to inspect their satellites to ensure military technology is not present. In return, each nation ensures that its adversaries pay a higher price for launching military equipment into space (via conventional rockets) and can place commercial and scientific payloads into orbit at a significant discount. Such a collective agreement will undoubtedly require sensitive negotiations between the different nations, particularly with respect to sensitive commercial technology and dual-use satellites (satellites with an ostensibly commercial or scientific nature that can be repurposed for military use). The impact of an inspection regime on trade agreements and other international treaties will need to be carefully examined. Difficult questions are also likely to arise regarding collective security for the space elevator (who will defend it from terrorist attacks?) but seem solvable (a floating platform hundreds of miles at sea is a difficult target for terrorists).

Finding common ground on these issues will not be easy, but there would be great incentive for a deal to be struck. Commercial interests alone – including from potential new industries like asteroid mining, space tourism, and telecommunications – would be powerful, and the fees levied on these commercial users of the space elevator could be distributed among the host nations to the benefit of all. Moreover, the same cost-ratio argument from above will disincentivize any country from attempting to seize the space elevator for military use in wartime. Why would a country risk seizing the space elevator for itself when it is unlikely to be able to defend it without incurring significant costs?

III. International political challenges to space elevator development

An international collaboration would have other benefits beyond reducing military risks, primarily by reducing technological risk. Even if a suitable tether material is discovered that can be produced at scale, the remaining engineering challenges (power beaming, tether repair, and climber design, just to name a few) are so significant that any given entity might be wary of taking on the risks by themselves. Private companies looking to build a space elevator would face tough questions from their investors about how the project would yield viable returns in a reasonable time frame. If governments attempted to go ahead on their own, the public could make similar judgments and ask whether the space elevator was worth the investment of taxpayer money.

A consortium of governments, scientists, and private corporations working together would help sidestep some of these concerns by spreading the cost and risk and preventing duplicative work. Such a cooperative scenario might include (for example) a tether built in the United States, climbers built in Japan, a power-beaming station built by European nations, and a floating platform built by China. This model is similar to the one used by the International Space Station (ISS), in which different modules are built and duties performed by partner nations (the United States, Europe, Japan, Russia, and Canada), each of which can send its astronauts and experiments aboard (International Space Station Intergovernmental Agreement 1998). Note that even traditionally adversarial countries – most prominently Russia and the United States – have been able to cooperate under the ISS framework, recent geopolitical tensions notwithstanding (Isachenkov and Dunn 2022). In return for the investment into the project, each partner nation would be given priority to use the elevator to launch its (peaceful) satellites, along with decision-making power over the space elevator policies and procedures. Non-partner countries without rocket-launch capabilities and commercial entities would pay a larger fee relative to the host nations to launch their satellites, with the funds being put towards maintenance of the space elevator as the tether degrades over time.

At the center of this collaboration are likely to be the US and Japan. Both governments have previously expressed interest in building a space elevator, as have private corporations in both countries (David 2014). The Obayashi Corporation in Japan – one of the largest private contractors in that country – has expressed a desire to build a space elevator by the year 2050 and is contributing funding and research to the effort (Matsunaka 2021). A Japanese team also recently demonstrated a climber moving between two tethered CubeSats in a space environment, although the cable was made of steel, and the distance traveled was only about 10 meters ("STARS Project" 2022). The US and Japan already work closely together in space (as demonstrated by the ISS framework) and have good diplomatic and scientific relations. China is likely to view such a collaboration with suspicion, and indeed has announced its own plans to launch a space elevator by 2045 (Reuters 2020). However, as noted above, parallel efforts to build a space elevator are likely to be inefficient, costly and could potentially lead to geopolitical conflict.

III. International political challenges to space elevator development

The possibility of a space elevator being constructed in the medium-term future must be taken seriously. Building a functioning space elevator would be a risky and costly endeavor, but the upsides are enormous. Should a suitable tether material be found, the biggest hurdles to constructing a space elevator are likely to be political, not technical. The dual-use nature of the space elevator means that nations will view it as a means to achieve military dominance in space, which may be destabilizing. Peaceful use of the space elevator, on the other hand, has great potential to revolutionize science and industry by dramatically reducing the costs of launching payload into orbit. An international cooperative framework for managing the space elevator should therefore be considered.

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