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# DESIGN AND DEPLOYMENT OF A SPACE ELEVATOR

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**Abstract**—The space elevator was first proposed in the 1960s as a method of getting into space. The initial studies of a space elevator outlined the basic concept of a cable strung between Earth and space but concluded that no material available at the time had the required properties to feasibly construct such a cable. With the discovery of carbon nanotubes in 1991 it is now possible to realistically discuss the construction of a space elevator. Although currently produced only in small quantities, carbon nanotubes appear to have the strength-to-mass ratio required for this endeavor. However, fabrication of the cable required is only one of the challenges in construction of a space elevator. Powering the climbers, surviving micrometeor impacts, lightning strikes and low-Earth–orbit debris collisions are some of the problems that are now as important to consider as the production of the carbon nanotube cable. We consider various aspects of a space elevator and find each of the problems that this endeavor will encounter can be solved with current or near-future technology. 

## 1. INTRODUCTION

In the exploration and use of space there is currently only one system that can deliver payloads to their destinations, rockets. However, during the first decades of the space age, 1960s and 1970s, an alternative means of getting to space was proposed, a space elevator [1–5]. The basic concept is to string a cable from the Earth's surface to an altitude beyond geosynchronous orbit (35,800 km altitude). The competing forces of gravity at the lower end and outward centrifugal acceleration at the farther end keep the cable under tension and stationary over a single position on Earth (Fig. 1). Theoretically, the cable could be constructed 144,000 km long and would be balanced in equilibrium [5]. However, placing a counterweight at the far end of a shorter cable, once the Earth end is anchored, would simplify construction and give the same stability. The cable would be tapered such that it is thickest at the point of highest tension (geosynchronous orbit) and thinnest where the tension is the lowest (at the ends) [5]. This cable, once deployed, can be ascended by mechanical means to Earth orbit. If a climber proceeds to the far end of the cable it would have sufficient energy to escape from Earth's gravity well simply by separating from the cable. The space elevator thus has the capability in theory to provide easy access to Earth orbit and most of the planets in our solar system [5].

## 2. CABLE FABRICATION

In 1991 the first carbon nanotubes were made [6]. These structures have promise of being the strongest material yet discovered (Table 1). This strength combined with the low density of the material makes it critically important when considering the design of a space elevator.

The tensile strength of carbon nanotubes has been theorized and simulated to be 130 GPa (see Table 1) compared to steel at $< 5$ GPa and Kevlar at 3.6 GPa. The density of the carbon nanotubes (1300 kg/m$^3$) is also lower than either steel (7900 kg/m$^3$) or Kevlar (1440 kg/m$^3$). The critical importance of these properties is seen in that the taper ratio of the cable is extremely dependent on the strength-to-weight ratio of the material used. (In our discussions the taper ratio refers to the cross-sectional area of the cable at geosynchronous compared to the cross-sectional area of the cable at Earth. A taper in the cable is required to provide the necessary support strength.) For example, based on Pearson's [5] work and operating at the breaking point, the taper ratio required for steel would be $1.7 \times 10^{33}$, for Kevlar the ratio would be approximately $2.6 \times 10^8$, and for carbon nanotubes the ratio is 1.5. Since the mass of the cable, to first order, is proportional to the taper ratio, carbon nanotubes dramatically improve the feasibility of producing the cable for a space elevator. In our discussions below we will implement a safety factor of two. This means that at all points the cable

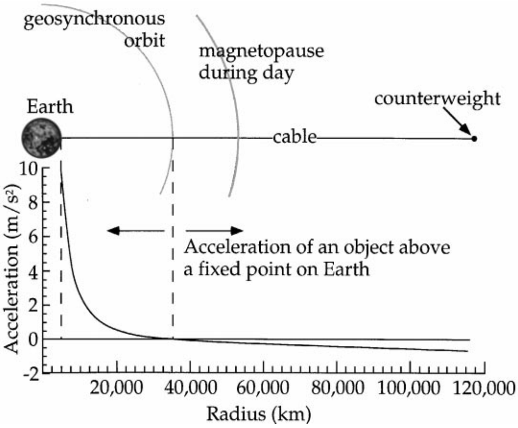


Fig. 1. Basic space elevator design: the basic space elevator concept and the effective acceleration as a function of position for an object stationary above a point on Earth. Positive accelerations are directed toward Earth while negative accelerations are directed away from Earth. The plot is based on Eqn. (2) from reference [3].

Table 1. Properties of carbon nanotubes

| | Theory | Measured |
|---|---|---|
| Density | 1300 kg/m$^3$ | — |
| Tensile strength | 130 GPa† | — |
| Melting temp. | 7800°C‡ | — |
| Resistivity | — | $1 \times 10^{-4}$ Ω cm§ |
| Young's modulus | 630 GPa† | 1800 Gpa‖ |

†Reference [7].
‡Reference [8].
§Reference [9].
‖Reference [10].

will have twice the strength needed to support the cable below it and the suspended mass of the climber.

Due to meteor impact considerations (see Section 4.1) we believe that a ribbon-type, epoxy/nanotube-composite design for the cable is optimal (Fig. 2). A ribbon for our discussions is a cable that is much smaller in one cross-sectional dimension than the other. The filling factors of standard composite materials are 60% fibers to 40% epoxy [11]. To further reduce the mass of the epoxy component in the cable it can be constructed with alternating sections of composite and bare nanotubes. To insure that the nanotubes are secure in the epoxy the composite sections must be much longer than the individual nanotube fibers and thick. This would imply a design that has composite segments of 100 μm or greater in length separated by sections of bare nanotubes millimeters to centimeters in length. This would allow the construction of a composite cable with less than 2% of its mass being epoxy.

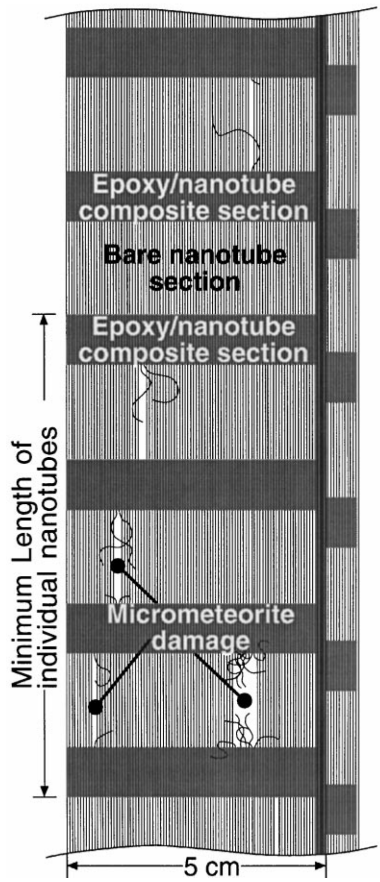


Fig. 2. Illustration (not to scale) of a ribbon cable with micrometeor damage and an additional ribbon epoxied to right edge.

This design would also imply that the minimum nanotube length that would allow construction of the cable is about 4 mm. One processing technique has produced several square centimeters of straight, parallel, tightly packed, nanotubes 50 μm long at rates of 120 μm/h [12]. A second production process has produced a tangled web of nanotubes 10 mm × 50 mm in less than 30 min [13].

## 3. SPACE ELEVATOR DEPLOYMENT

In considering the deployment of a space elevator we can break the problem into three largely independent stages: (1) deploy a minimal cable, (2) increase this minimal cable to a useful capability, and (3) utilize the cable for accessing space.

### 3.1. *Initial cable deployment*

Based on previous and on-going work, there are three fixed design components that we will adopt for our discussions. First, our space elevator design will be based on carbon nanotube technology as stated above. Second, our cable design will

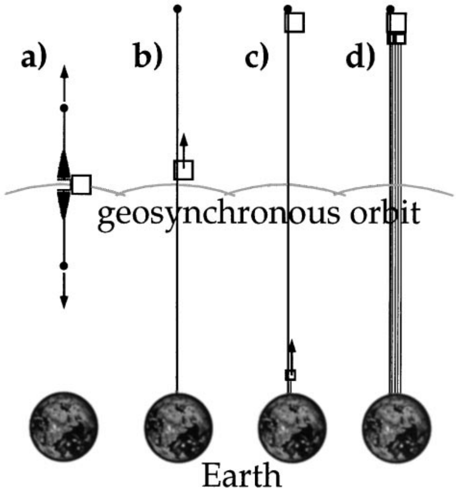


Fig. 3. Deployment of a space elevator: (a) unspooling of an initial cable from a spacecraft in geosynchronous orbit. Ends of a spooled cable are deployed upward and downward. (b) Once the initial cable is deployed and anchored the spacecraft moves upward. (c) After the spacecraft reaches the far end of the cable it acts as a counterweight. Climbers can now be attached to the cable and ascend. (d) A useful cable is realized after successive climbers reach the far end of the cable and increase the cable's overall lift capability.

be tapered as presented by Isaacs et al. [2] and Pearson [5]. Third, deployment of the initial cable will be from geosynchronous orbit [2].

Deployment of the initial cable will entail placing a spacecraft carrying a spooled cable in geosynchronous orbit. The cable will be on two spindles such that each end can be deployed separately, one end downward toward Earth (pulled by gravity) and the second upward (pulled by outward centrifugal acceleration, Fig. 3). Once both ends are fully extended, the end at Earth is retrieved and anchored. After the cable is anchored the spacecraft bus that has been at geosynchronous orbit moves outward along the cable to become the counterweight at the far end of the cable. This will complete deployment of a stable, small, initial cable under tension. The details of this deployment are the topic of our next section.

Since the problem we are discussing is the feasibility of constructing a space elevator we will constrain ourselves to using current or near-future technology. Selecting the largest (US) launch vehicle available, a Titan IV/Centaur, it is possible to place a 5500 kg payload into geosynchronous orbit. The payload in this case consists of a cable, its deployment mechanism, and a spacecraft bus. The spacecraft will require only low communication rates, loose attitude control and low-power requirements. The deployment system will be required to deploy the cable in a controlled method, and join cable segments on orbit. For a baseline, a spacecraft such as Forté can be used [14]. Forté is a small mission with roughly the size and capabilities that are required here for the spacecraft bus. The primary difference is the payload mass. Aspects of the Forté mission that match with our discussion include the carbon composite space frame, solar power, basic attitude control, communications and command systems. The mass breakdown for Forté can be seen in Table 2. If we start with this baseline we can make a crude estimate of what would be available and required for the spacecraft we are examining. The largest uncertainty and mass is in the support structures for the cable. The spindles on which the cable is stored will need to support a 5000 kg cable during launch (see below). With proper orientation to the maximum launch forces this support may be a simple design. If a larger support structure is required the initial cable would need to be reduced in length and slightly in capability as can be determined from Fig. 4.

Since we will also need a countermass once the cable is deployed we will retain the spent Centaur upper stage (3440 kg). With the Titan IV/Centaur

Table 2. Forté mass breakdown

| | Mass (kg) | Mass (kg) for initial cable SC |
|---|---|---|
| Structures | 56 | 300 |
| Payload | 74 | 5000 |
| Power | 36 | 50 |
| Att. control | 14 | 50 |
| Command | 6 | 15 |
| Comm. | 3 | 10 |
| Thermal | 15 | 20 |
| Total | 204 | 5445 |
| Total w/o payload | 130 | 445 |

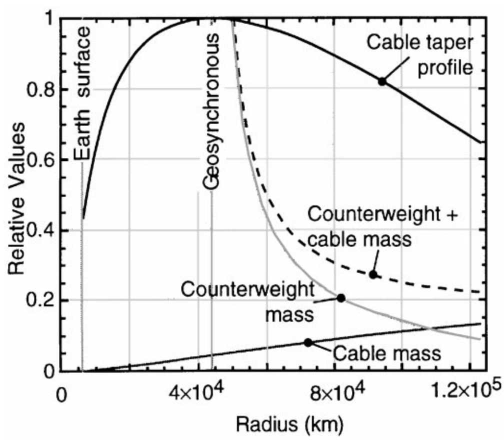


Fig. 4. Taper profile and mass distribution. The diameter taper profile and relative masses are shown for a cable extending up to the given radius from Earth center.

launch envelope of 5500 kg we find that we can deploy a nanotube ribbon that is 1.5 μm by 5 cm at Earth and tapering to 1.5 μm by 11.5 cm at geosynchronous (Fig. 4) with a total length of 117,000 km and a total mass of 5000 kg. This cable has the capability of supporting a 132 kg climber. Cable segments can be launched individually and combined on-orbit allowing a larger climber capability. As an example, in the following discussions four Titan IV/Centaur launches will be used as a baseline for deploying an initial cable where climbers of 528 kg each can be utilized within our factor of two safety margin.

*3.2. Climbing stage*

The next stage is to increase this minimal cable to a useful capability. During this stage climbers will ascend the cable and deploy additional cables as they climb. The climbers must be able to carry the entire additional fiber and spool it out as they climb.

Using the same length as in the initially deployed cable, the counterweight to cable mass split is 212 kg for the counterweight and 316 kg for the cable. With this mass the cable would be 1.5 × 694 μm and add 7.96 kg to the lift capability of the initial cable. This is a 1.5% increase in the lift capability of the cable. Climbers can be sent up when the previous climber has reached the 0.1 g point (13,000 km altitude). The travel time of a climber before the next climber initiates its ascent is critical for two competing reasons. First, the travel time is inversely proportional to the climbing power required. Second, the initial cable has a finite life (see Section 4.1) so climbers must strengthen the cable quickly. As an example, we will examine a climber that will satisfy both of these requirements ascending to geosynchronous orbit with a 1 week travel time.

To climb the cable to geosynchronous in 1 week requires an average of 80 W/kg of mechanical climbing power. The simplest system design has a constant power and variable speed transmission. With constant power the climber's ascent speed will change dramatically from 37 km/h at the ground to over 10,000 km/h before geosynchronous orbit. The time determining velocity is that below the 0.1 g point before the next climber begins its ascent. For this reason no velocities above 200 km/h will improve the construction time of the cable in our scenario so none will be used in our discussion. Beyond geosynchronous the climber will "fall" to the far end of the cable without additional power where it will become a counterweight. For our 528 kg climber this implies 42 kW average mechanical power and the ascent to the 0.1 g point will be 116 h. If a climber is sent up the cable every 116 h and increases the cable strength by 1.5% then the lifting capability of the cable would double every 232 days.

For the locomotive system our design is based on a simple DC electric motor with a variable transmission attached to a set of rollers to pull the climber up the fiber. Off-the-shelf electric motors have mechanical power to mass ratios of 566 W/kg and can be 91.7% efficient in converting DC electrical to mechanical energy [15]. Thus, the motor part of the climber would have a mass of 75 kg and require 46 kW of input electrical power for the 42 kW of climbing power.

There are two feasible power delivery systems: (1) microwave power beaming, and (2) laser power beaming.

*3.2.1. Microwave power beaming.* Several studies have been conducted on the beaming of power from space using microwaves [16,17]. These studies have looked at frequencies of 2.4, 35 and 94 GHz primarily and utilize dish, flat or phased array transmitting and receiving antenna [16,18]. If we consider our specific situation of beaming power to space and not from space in these same terms we start with the equation

$$\frac{P_r}{P_t} = \frac{A_r A_t}{d^2 \lambda^2},$$

where $P_r$ is the power received, $P_t$ is the power transmitted, $A_r$ is the area of the receiving antenna, $A_t$ is the area of the transmitting antenna, $d$ is the distance between the transmitting and receiving antenna and $\lambda$ is the wavelength. A low-mass receiving antenna is required so we will select a baseline 3 m diameter area ($A_r = 7\ \mathrm{m}^2$), 50 kW delivered to an altitude of 15,000 km (for the initial climber, 40 times this for the final climbers), and a phased array transmitting antenna of $1 \times 10^6\ \mathrm{m}^2$ ($1\ \mathrm{km}^2$). Including rectenna efficiency (50% [18,19]) and transmission efficiency (30% [17]) we find we will need $1.7 \times 10^5$, 792, and 110 MW, going to the transmitters for 2.4 ($\lambda = 12.5$ cm), 35 ($\lambda = 8.6$ mm), and 94 ($\lambda = 3.2$ mm) GHz, respectively, for the first climbers. This system is easily expandable as required and the transmitted power is inversely proportional to the transmitting antenna area. A frequency of 94 GHz is preferable from the numbers above. Considerable effort has gone into developing rectifying antenna at 35 GHz for use as lightweight receivers. These rectennas have 50% total efficiency [18] and similar results should be achievable at 94 GHz [19]. The mass of the rectenna would be comparable to lightweight solar panels at 33 kg for a 50 kW receiver [19]. A possible alternative microwave beaming system is to utilize a maser as proposed by Caplan [20]. Microwaves at frequencies above 10 GHz are readily absorbed by water vapor, so careful high-altitude site selection is required (see Section 4.6).

*3.2.2. Laser power beaming.* One system that has been proposed for use with conventional satellites utilizes large diode laser arrays [21]. Kwon's [21] concept utilizes 2000–5 W diodes in a large-scale amplifier array operating at 800 nm. The simulations of this expandable system show that 80% of the transmitted power can be delivered into a 3 m diameter area at 10,000 km (ignoring atmospheric blooming, see below and Section 4.6). This power could be received by tuned solar cells that have been demonstrated to operate with 59% efficiency and 82% filling factor at 826 nm with maximum power densities of 54 $W/cm^2$ [22]. Based on conventional solar cells the mass of the receiver would be 21 kg (7 $m^2$ at 3 kg/m). The delivery system would require some additional work to keep the required receiver area from expanding with the necessary increase in power. Thermal control of the receiving solar panels would also be required to maintain the quoted performance. The atmospheric distortion in the laser transmission would be 2 μrad from a 6 km altitude location. This distortion would seriously degrade the power transmission (2 μrad corresponds to 20 m at 10,000 km) so adaptive optics would be required.

After accounting for the mass of the cable, motors and power receiver we have 104 kg (out of 212 kg), for the structures, transmission and rollers, control, and remainder of the climber. This is a tight mass budget but should be feasible in a simple system that may require no communications, no attitude control, not be required to survive a violent launch, and have a very basic set of instructions.

With the continuous power that is beamed to the climbers heat will be generated in both the power receiving system and in the locomotion system. This power will be up to 32 W/kg if the laser beaming system is used. This does not include frictional affects, solar heating or other parasitic heating sources.

A new power generation facility would also be required in the region where the power beaming system is located. This could be any of several sources (oil, hydroelectric, wind, solar, etc.) but would need to supply up to 4 GW, depending on the power beaming system and overall system design.

After 250 climbers (40 months) have been sent up the cable with incrementally increasing cable payloads, the cable would be capable of supporting a 20,000 kg climber (13,000 kg payloads) in route to Earth orbit or any space location within the orbit of Saturn every 5 days. This payload mass is 2.4 times the launch capability of the Titan IV/Centaur to geosynchronous.

### *3.3. Utilization stage*

The primary use of an initial 20,000 kg cable may be to place spacecraft into low-Earth through geosynchronous orbits. The recurring costs of this system would be the cost of the climber to transport the payload. Additional cables of comparable capacity could be produced every 232 days using this first cable and "shipped" to other sites along the equator by dragging the lower end of the cable. In 3.5 years the capacity of any individual 20,000 kg cable could be built up to $1 \times 10^6$ kg. In addition, as pointed out by Pearson [5], spacecraft could be launched to the moon and all but the furthest planets simply by being released from the end of the cable at the appropriate time.

## 4. SPECIFICS OF THE SYSTEM DESIGN

### *4.1. Micrometeorite impacts on cable*

One of the primary concerns for the durability of a space elevator is the destruction of the cable by micrometeorite impacts and low-Earth-orbit debris.

We have used the micrometeorite fluxes compiled by Manning [23] to calculate the frequency of impacts on cables with their largest dimension being 36 μm, 1 and 5 cm. We will assume that micrometeors will destroy areas larger than their cross-sectional area and pass through the ribbon cable. From Figs. 5 and 6 we can see that Earth-to-space cables with maximum dimensions of less than several centimeters will be destroyed within weeks. Thus, the cable must be intimately bundled (a composite) to survive the large number of small micrometeors yet have at least one cross-sectional dimension greater than 5 cm to survive long enough for reinforcing cables to be put in place. The best alternative for the initial cable is a 5 cm × 1.5 μm or greater aspect ratio ribbon. With this ribbon, meteors up to 1 cm can pass through the ribbon with roughly a 25% strength degradation at any point (Fig. 2). Meteors larger than 2 cm (one impact per 10 yr) could destroy the ribbon. The rate at which the degradation of

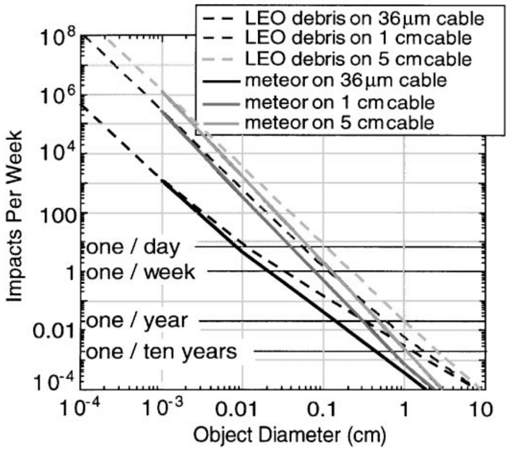


Fig. 5. Impacts per week average for various particle and cable dimensions. Based on meteor flux data [21] and LEO debris data [22].

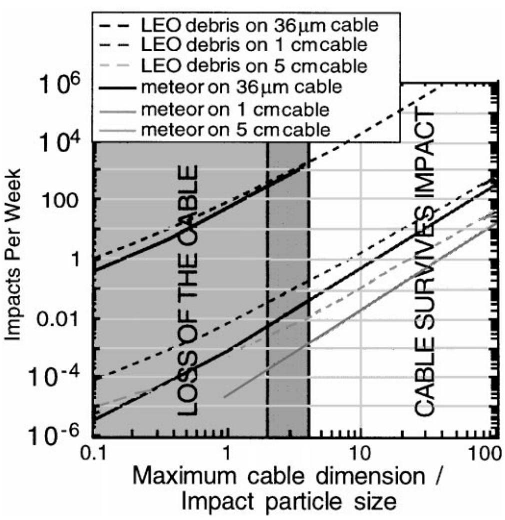


Fig. 6. Plot of impacts per week versus the ratio of maximum cable dimension to the size of the impacting object. If the object is one-half the maximum cable dimension the cable will be severed. Objects with diameters up to and beyond one-quarter the maximum dimension of the cable may sever it. Based on meteor flux data [21] and LEO debris data [22].

the fibers occurs determines how quickly climbers must ascend the cable to increase its size. Once the size reaches many centimeters in its largest cross-sectional dimension degradation is minimal.

### 4.2. *Low-Earth-orbit spacecraft impacts on cable*

If we assume a collisional cross-section for a low-Earth orbiting spacecraft of 2 m we find the chances of an individual low-Earth-orbit (LEO)

Table 3. LEO collision avoidance

| Tracking accuracy (m) | Time between required cable movement | Size of movement required (m) |
|---|---|---|
| 1000 | 12 h | 1000 |
| 100 | 5 days | 100 |
| 10 | 50 days | 10 |
| 1 | 50 days | 10 |

spacecraft hitting the cable on any random orbit is $5 \times 10^{-8}$ or $2.6 \times 10^{-4}$/yr in orbit for each individual space craft. This is not a significant threat for LEO spacecraft considering orbital lifetimes of a few years but depending on the number of LEO spacecraft to be launched in the upcoming years it could limit the lifetime of the space elevator. With 8000 LEO objects 10 cm in diameter or larger it would be expected that the cable would be hit once every year. One method to reduce the possibility of collision is to make the anchor end of the cable movable and actively avoid collisions. A 100 m movement of the anchor would translate into a comparable movement at low-Earth orbit with some time delay. LEO objects with orbit inclinations of $> 30^\circ$ are currently tracked by NORAD. Since there are LEO objects with orbit inclinations of $< 30^\circ$ that could jeopardize the cable a new object tracking network would be required. Radar and advanced tracking methods [24,25] can provide position information with hundreds of meters accuracy for most objects of interest. This tracking would allow minimal movement to avoid impacts by LEO objects (see Table 3).

### 4.3. *Radiation damage of cable*

The segment of the cable in Earth's radiation belts will experience less than 3 Mrad/yr (energetic electrons and protons) [26]. Studies of epoxy/carbon fiber composites (epoxy/nanotube composites would be expected to be comparable) have found them to be radiation hard to greater than $10^4$ Mrad [27,28] which would allow them to survive more than 1000 years in the expected environment.

Atomic oxygen poses a more serious space environment problem for the cable. Atomic oxygen erosion of epoxy/carbon fiber composites have been seen at rates of 1 µm/month in low-Earth orbit [29]. A suggested solution is to coat the composite with a material resistant to atomic oxygen [29]. Possible candidates include aluminum and ceramic. Thin layers of these protective coatings (100s of Å) would be required on the cable only for altitudes where the atomic oxygen flux is high.

### 4.4. Cable heating by magnetic-field-induced electrical currents

Heating of the cable can be produced by passage through the local magnetic fields. The potential induced along the cable can be expressed as

$$E = B(r)v(r),$$

where $E$ is in V/m, $B(r)$ the magnetic field, and $v(r)$ the velocity of the cable relative to the magnetic field. For radii $(r) < 10r_{\mathrm{Earth}}$, $B(r) \sim 0.35 \times 10^{-4} r_{\mathrm{Earth}}^3/r^3$ and $v(r)$ is approximately zero. However, if we assume the worst possible case where the magnetic field is fixed and the cable is rotating with the Earth ($v(r) = 463r/r_{\mathrm{Earth}}$ m/s) we get potentials from 0.00026 V/m at $10r_{\mathrm{Earth}}$ to 0.016 V/m at Earth's surface. At distances of greater than $10r_{\mathrm{E}}$, the cable is in the interplanetary magnetic field during the day ($B_{\mathrm{ave}} \sim 6$ nT and $B_{\mathrm{max}} \sim 80$ nT) and is in the Earth's magnetosphere at night (Fig. 1). This corresponds to a maximum potential of 0.00068 V/m at the far end of the cable. With a minimum resistance of 0.4 Ω/m we have a maximum of 0.0064 W/m of heating occurring near the Earth end of the cable and 1 μW at the far end. The cable would quickly radiate this level of heating away into space.

### 4.5. Natural frequency and oscillations in the cable

Initial work on the oscillations induced by the Moon, the motion of climbers and Earth's atmosphere have been discussed in Pearson [5] and the problems associated with each appears to be avoidable.

The first longitudinal vibration period of the proposed cable (taper of 2.3) would be approximately 10 h based on Pearson's [5] calculations which is close to the excitation period of the Moon. Variations in the counterweight location and active damping at the anchor of this mode can be used to eliminate this oscillation problem.

The first lateral oscillation mode has a period of approximately 47 s [5] which prohibits climbers traveling at a constant 5 km/s (18,000 km/h). This is not a problem in our proposed scenario.

### 4.6. Deployment locations

The anchor location of the cable must be near the equator but no hard limits on the latitude tolerance have been found. Anchor locations off the equator will place a constant out-of-plane force on the cable and counterweight and an additional time-variant force when climbers are on the cable.

One consideration for location of the cable is for power transmission to the climbers. At altitudes above 6 km [30] the absorption of microwaves (0–300 GHz) due to water is negligible and transmission is above 90% for a large fraction of the 0–300 GHz range. This reduction of water and total atmosphere would also reduce the atmospheric thermal-blooming for laser transmission if that system is selected. Human operation of a power beaming station at these altitudes becomes difficult so a lower altitude of 5 km may be required. Optimally, the power beaming station would be located within 10 s of km of the anchor point to allow for line of sight transmission at the lower altitudes (a smaller power beaming station can be located at the anchor point to initiate the climb).

A second consideration for the anchor location is general weather considerations. The jet streams and severe storms (cyclones) may damage the cable. Based on wind force calculations by Pearson [5] we find that the total wind loading on the initial cable in the worse case (face on to the ribbon and maximum wind velocity for cyclone) is $1.25 \times 10^6$ N. This force is sufficient to overload the cable and possibly damage it. However, by selecting an equatorial site we avoid both the jet streams and cyclonic storms.

A third consideration for the anchor location is the frequency of lightning strikes. Since the cable will create a conductive path from the atmosphere to the ground it could be a conduit for lightning. The high electrical currents produced in a lightning strike, if run through the cable, would destroy the cable through extreme heating. Lightning strikes are prevalent across the surface of Earth with two possibly useful exceptions: (1) high elevation sites, and (2) ocean sites. The only study of lightning strikes as a function of underlying ground elevation that extended above 4 km [31] shows that the frequency of lightning strikes decreased at higher elevations and found only one cloud-to-ground lightning strike above 5 km over a 13-year period. A note of caution, however, this study was conducted in Alaska which is very different from equatorial locations in terms of climatology. However, on global lightning distribution maps [32] a general anti-correlation between the frequency of lightning strikes and ground elevation can be seen in relation to the Andes, Himalayas, Alps, mountains of eastern Africa, and Rocky mountains. It has also been observed that lightning strikes (intracloud and ground to cloud) are much less prevalent over particular ocean areas [32]. One notable location near the equator with the lowest

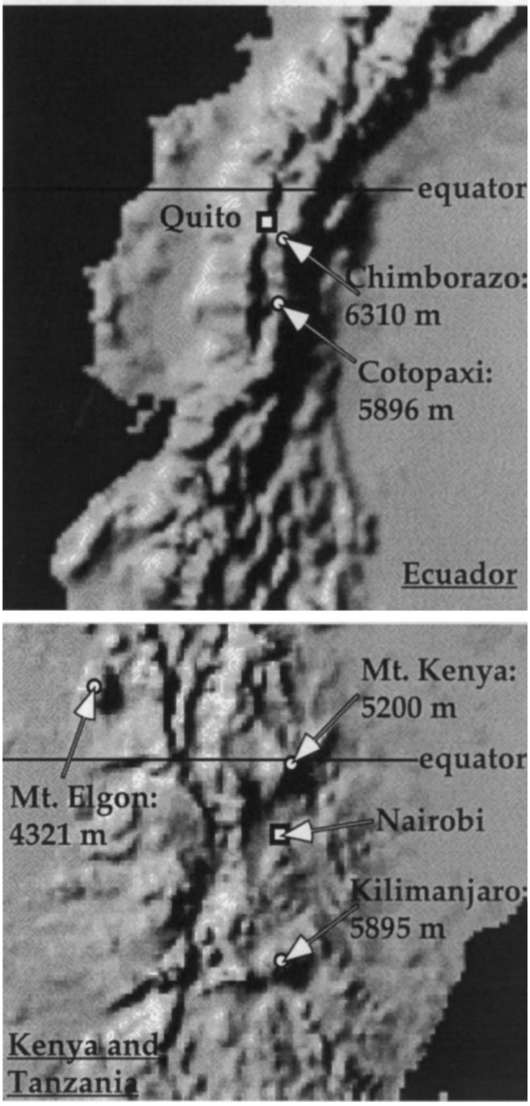


Fig. 7. Topographic maps of the regions near Quito, Ecuador (upper map) and Western Africa (lower map) where good anchor points are located. Maps are a product of the USGS website.

occurrence of lightning is in the eastern Pacific off the coast of Ecuador. A second smaller region is located off the Tanzanian coast.

Ignoring tesseral harmonic perturbations, optimal land locations appear to be in Ecuador, or possibly several mountain sites in Kenya and Tanzania (Fig. 7). However, because of the problem with lightning a floating anchor site in the Pacific off the northwest coast of South America may be preferable while the corresponding power beaming station would be located in Ecuador's coastal mountains. Further detailed studies of the distribution of lightning strikes are required before a final site selection can be made.

### *4.7. Risks of severed cables and malfunctioning climbers*

In several cases discussed it is possible that the cable may become severed. Independent of where the cable severs, the lower end will fall back to Earth. If the break is caused by a low-Earth orbit object then several hundred kilometers of cable will fall near and east of the anchor point and the upper segment of the cable will be thrown out of Earth orbit. If the break occurs at the far end of the cable, the entire cable will fall back toward Earth eastward of the anchor point. However, since epoxy used in composites can disintegrate at 120°C the ribbon can be designed to separate in the atmosphere on re-entry leaving only small segments of individual 1 μm diameter fibers millimeters in length to fall to the ground. The environmental impact of 200, 000 kg of small fibers spread out over the planet still needs to be examined. One possible solution to reduce the risk of losing the cable to this circumstance would be to shorten the cable and use a larger counterweight once the initial cable is up and in place. This would reduce the impact cross-section of the cable above goesynchronous orbit by a factor of 3. The down side of this tactic is to reduce the ease of launching spacecraft out of Earth orbit.

Another problem could occur if a climber were to seize during its ascent. If this were to occur at a low altitude (possibly up to 1000 km depending on cable safety margin) the cable could be reeled in until the climber is retrieved and then the cable would be allowed to float back out to its nominal position. Above the lower altitudes the cable could not be reeled in far enough without risking breakage. Above the $0.7g$ (1400 km) point a second climber without payload could be sent up to release the malfunctioning climber and carry it to beyond geosynchronous orbit where it could be released. Between LEO and $0.7g$ the cable may be floated out sufficiently for the seized climber to be above the $0.7g$ point and a second climber can then be sent up to retrieve it.

## 5. CONCLUSIONS

The space elevator has tremendous potential for improving access to Earth orbit, space and the other planets. When originally proposed this potential appeared to be in the distant future constrained by the lack of viable materials. Carbon nanotubes with theoretical strength-to-mass ratio sufficient for construction of the space elevator are now being produced in small quantities and work is proceeding to fabricate longer nanotubes in greater quantity.

As this work proceeds a space elevator will become viable. The feasibility of the space elevator then hinges on the other aspects of its design, construction, deployment and utilization. We have presented the various aspects of the space elevator along with the problems and possible solutions associated with each. In our examination we found none of the possible problems unsolvable with current or near-future technology but further, detailed studies are required.

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