Approaching the Final Frontier

Near Space

The Space Elevator

Today, payloads are hurled into space on (still) expensive rockets. To get the best performance, these rockets push their design to the limit. And, as a result, considerable time and many people are required to build and prepare a rocket for launch. It's the cost of paying salaries that makes rocket launches so expensive; rocket fuel is actually cheap.

While an airplane is reusable — a feature which offsets the plane's high initial cost — so far, no rocket is totally reusable. Imagine how long an airline carrier would stay in business if it took a thousand people six months to get one of their airplanes ready for flight, and then they threw away a major chunk of the airplane in the process of getting it across the country.

Is there a better alternative to sending cargo into space on rockets? Many people think so. This article discusses one possible solution: the Space Elevator (SE).

Introduction

"Reach low Earth orbit and you're half way to anywhere in the Solar System."

— Robert Heinlein

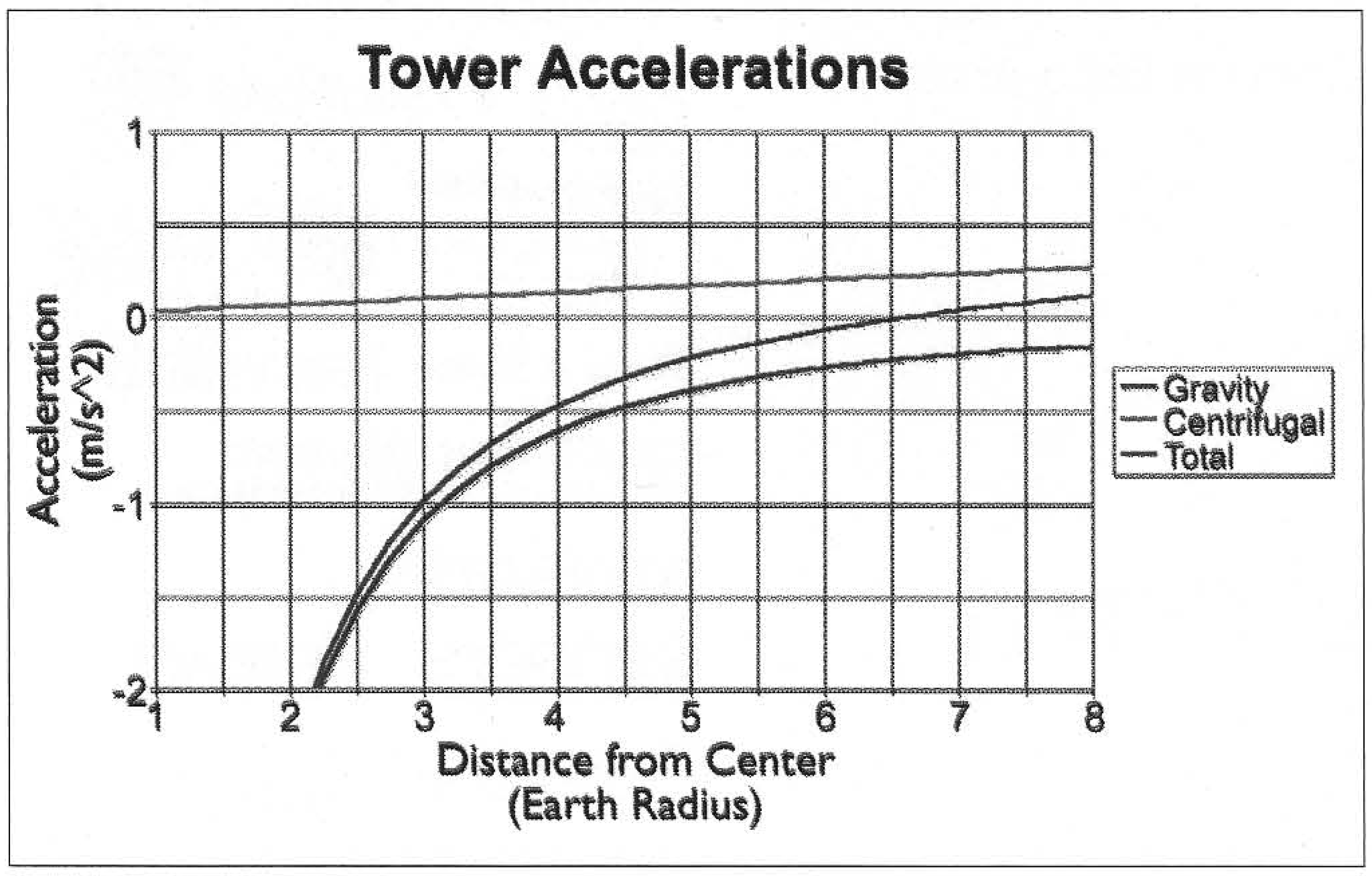
The concept of the Space Elevator has been around a very long time. Stories like Jack and the Beanstalk reflect the popularity of reaching extreme altitudes by climbing tall towers. Today's version of this dream is the SE. The SE is a device for sending a payload into space without the fuss or muss of a rocket launch. The SE, as envisioned by its supporters, would create airline-like service to Earth orbit. But, before describing the SE in detail, let's briefly look at its history.

History

The oldest mention of the SE that I have come across is by Konstantin Tsiolkovsky. A high school teacher before the Russian Revolution, Tsiolkovsky single-handedly developed most of the space travel concepts we take for granted. His book, *Day-Dreams of Heaven and Earth* (1895), explains what happens as you climb an extraordinarily tall tower. His reasoning and results went like this:

There are two forces acting on a body standing on a rotating body: gravity and centrifugal force. Earth's gravity pulls you towards the center of the planet. The reach of gravity is infinite, although weaker as you move farther away. The only reason astronauts float inside the Space Shuttle is that both they and the spacecraft are in free fall around Earth. Stop the Shuttle's motion, and gravity will reappear for the astronauts — although weaker because of the Shuttle's 300-mile altitude.

Figure 1. As you can see, objects experience no net acceleration at a point 6.62 times Earth's radius away from the center, or 22,255 miles above the ground.



Your momentum, generated by the rotation of Earth, will fling you eastward if Earth's rotation is halted. Your motion, when it's viewed from a rotating frame of reference (like the rotating Earth), has the appearance of a force directed away from the center of Earth. This pseudo-force is called centrifugal force. However, to an inertial frame of reference, one that is moving at a constant speed and direction, there is no centrifugal force — there's only gravity and your momentum. Unlike gravity, centrifugal force is not a true force. It's only used to simplify kinematic problems on a non-inertial frame of reference, like a rotating planet.

Forces, like gravity and centrifugal force, create acceleration. The acceleration due to gravity depends on the mass of Earth, the inverse of the square of the distance from its center, and a constant called the Gravitational Constant (G). The following equation calculates the acceleration due to gravity (A_g) in meters per second squared (m/s^2) when the radius from the center of Earth is given in meters.

$$A_G = G \text{ X } M_e / (R_e + h)^2$$

Equation 1

where the term, $R_e + h$, is the radius of Earth (6,380,000 meters) plus your height above sea level and,

G is 6.67×10^{-11}
M is 5.98×10^{24}

Doubling your distance from the center of Earth (not the altitude above sea level) decreases the force of gravity, the acceleration it creates, and your weight by a factor of four, that is, $1/2^2 = 1/4$. With Equation 1, I calculate that one of my near spacecraft at an altitude of 100,000 feet experiences a 1% reduction in Earth's gravity.

The acceleration due to centrifugal force depends on your velocity squared and the inverse of your distance from the center of rotation, or,

$$A_C = V^2 / (R_e + h)$$

Equation 2

When standing on a tower fixed to Earth's surface, your orbital period around Earth remains fixed at 23 hours and 56 seconds (rounded to 24 hours or 86,400 seconds). You can calculate your velocity by multiplying the height of the tower above the center of Earth ($R_e + h$) by two times pi and dividing by the length of a day in seconds (86,400 seconds).

$$V = (2 \times pi \times (R_e + h)) / 86{,}400$$

Equation 3

Substituting the equation for velocity (Equation 3) into the equation for acceleration (Equation 2) creates a single equation for calculating the centripetal acceleration,

$$A_C = (4 \times pi^2 \times (R_e + h)) / 86{,}400^2$$

Equation 4

To determine the effect of climbing a tall tower, we combine the effects of gravity and centrifugal force. By combining the accelerations due to gravity (towards the center of Earth) and centrifugal force (away from the center of Earth), I was able to generate the following chart (shown in Figure 1) of total (or net) acceleration as a function of height above the center of Earth.

Tsiolkovsky's SE was a tower tall enough to reach a stationary orbit for the planet it stood on. Cargo rode up the tower until it was in geostationary orbit and able to be released without crashing back to Earth.

Now, Tsiolkovsky didn't think it was possible to build a SE. For one reason, building a tower taller increases its weight. In order to remain standing, as the tower's weight increases, its strength must also increase. Without changing the nature of the tower, its strength is increased by widening it.

Since the weight of the tower increases as you approach the surface of Earth, the tower must get wider as you approach its base. However, widening a tower's base adds weight to the tower which, in turn, requires the tower's base to be even wider. At some point, we reach the maximum height permitted by the tower's construction and materials.

Yuri Artsutanov, a Leningrad engineer, performed the first serious engineering study of the SE in his paper, "Into Space with the Help of an Electric Locomotive." His study was published in 1960 in the pages of the Soviet newspaper *Pravda*. No one took notice of his results, perhaps as a result of publishing his study in a habitually dishonest newspaper.

Artsutanov's initial SE was one millimeter wide and capable of carrying 900 tons of cargo into geostationary orbit (I believe this is 900 tons per day). The beauty of Artsutanov's SE is that it can bootstrap itself. Only a thin ribbon needs to be flown into space. The tower's climbers then make trips up and down the SE, adding additional ribbons each trip. Once the SE was a thousand-fold stronger, it could lift 12,000 tons of goods per day to geostationary orbit, or the equivalent of one fully loaded Space Shuttle launch every four minutes.

A 1960s Convair feasibility study on the use of tall towers for astronomy, high altitude research, rocket launching, and communications determined that the tallest possible

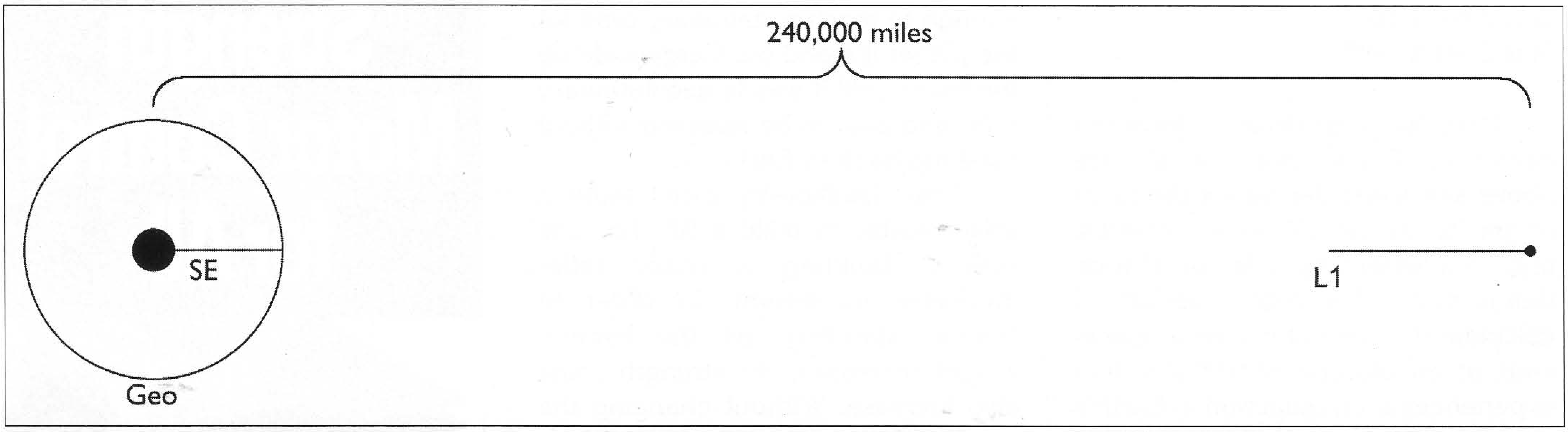


Figure 2. A very close-to-scale drawing of the Earth and Moon. Depicted are a SE, geostationary orbit, and a lunar elevator. *(Note: I did this diagram before I realized that the SE would extend above geostationary orbit in order to be put under tension. So in this diagram, the SE extends farther.)*

steel tower is 3.7 miles and the tallest aluminum tower is 6.2 miles. Graphite composite is stronger than an equal weight of steel. As a result, the tallest a graphite composite tower can reach is an altitude of 24.8 miles. A graphite composite tower of this height requires a base 3.7 miles wide. Currently, the tallest artificial structure is the KTHI TV radio tower. Made of steel, it stands 2,063 feet tall. We only need to increase its height by a factor of 55,600 to turn it into a SE.

At a 1963 presentation at the Ames Research Center, Arthur C. Clarke told his audience to think of a satellite in geostationary orbit as standing on a tall tower. Jerome Peterson was listening that day and thought, why not actually built a tower that tall?

Today, Pearson's company, Star Technology and Research, has developed an SE concept with the help of a $75,000 award from NASA.

Pearson's Lunar Space Elevator

Pearson proposes constructing the first SE on the Moon. With its lower gravity (1/6th of Earth's), the tower's weight is lower and this reduces its strength requirement.

As anyone who has observed the Moon knows, the Moon keeps its same face pointed towards Earth, though there's a slight wobbling called libration. Since the Moon doesn't rotate, there's no such thing as a geostationary (lunastationary?) orbit around the Moon. However, there is a point where the gravity of Earth balances both the gravity of the Moon and the centrifugal force of the Moon being in orbit around Earth.

This balance point creates a location where a satellite remains stationary above the Moon and with respect to Earth. This point is called the First Lagrangian Point, or L-1, and is located on a line between the Earth and Moon 36,039 miles above the center of the Moon with respect to us on Earth (see Figure 2).

If you plot the direction of the forces surrounding the L-1 position, you'll find that L-1 is more like a hill than a bowl. A marble remains stationary at the top of a hill, but give it a little shove and it becomes unstable and rolls away. The same is true of a satellite located at L-1. To remain at L-1, a satellite, or tower, requires active maintenance of its position.

There are four additional stationary points located within the Earth-Moon system and two of them, L-4 and L-5, are stable like a marble is at the bottom of a bowl. L-4 and L-5 will make great locations for space colonies and industry.

Materials strong enough to form a 36,000-mile-tall tower above the lunar surface exist today. Spectra (a kite string I use) and Kevlar are two of the suitable materials with which you're probably familiar. Pearson believes the best material is a fiber manufactured by Magellan Systems called M5. A 36,000-mile-long lunar SE made of M5, and with the strength to lift a climber and 400 pounds of payload, weighs only 15,000 pounds. That is small enough to be carried by a single Space Shuttle launch.

The climb up a lunar SE is slow, so it's not suitable for transporting people. However, the Moon contains resources useful for space colonies and exploration. A commodity like ice trapped at the lunar poles is useful as fuel and water. The Moon's raw dirt (regolith) is valuable as a shielding material for space colonies. To reduce the time required to haul lunar ice from the lunar poles to the lunar SE, a second lunar SE can be set up from a lunar pole to the L-1 position.

So engineering models show that the lunar SE is feasible today, but what about a SE on Earth?

Back to the Earth-based SE

Otis, the elevator company, has developed the technology for five-mile high elevators. Within 10 years, they believe they can develop the technology for an elevator that can climb to geostationary orbit on an SE.

Several SE papers were presented at the 55th Astronautical Congress in 2004. Several of the papers focused on an Earth SE constructed as described below.

The SE of the future begins as a 15-centimeter-wide ribbon launched into geostationary orbit. The ribbon bootstraps itself until it's a one-meter-wide ribbon. The base of the ribbon is tethered to a floating ocean platform, where it's protected from acts of terrorism and from the political upheavals possible in countries with unstable governments.

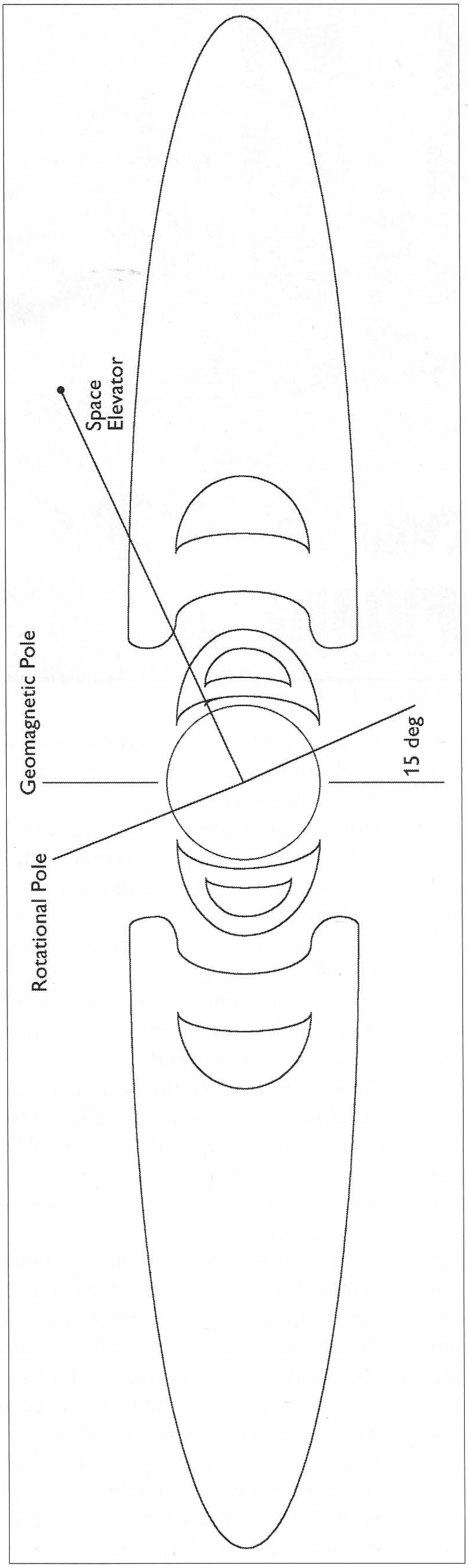
An additional benefit of tethering the SE to a floating platform is that there are equatorial regions where peaceful weather is the norm. For instance, hurricanes cannot form on the equator because the Coriolis Effect is nonexistent there. Orbital predictions are used to schedule movements of the floating platform in order to avoid orbital collisions between the ribbon and satellites.

Cargo is sent up the SE inside a climber — a climbing robot. SE climbers carry a photovoltaic array for power. Electrical power is beamed to climbers via lasers. Climbers use the electricity to scale the SE ribbon with a set of pinching rollers. Solid-state continuous lasers with 1 kW output currently exist and have efficiencies of 30%.

Combined laser modules form the SE power station. The ribbon is made from carbon nanotube (CNT) fibers embedded within a matrix. CNTs of the required strength exist today. To support the weight of the SE and its climbers, the SE ribbon must have a strength of 100 GPa. Current CNTs have a strength of 200 GPa, but only a length measured in millimeters.

The climbers are multi-functional robots. Not only do they climb the ribbon, but they also lay ribbon, identify ribbon damage, repair ribbon damage, and rescue stranded climbers. Transit time to geostationary orbit is 500 hours, so it's not a convenient system to carry people into orbit. Climbers must be reliable, as they'll climb for 500 hours without stopping to reach the top of the SE.

Figure 3. A diagram of Earth's radiation belts.



Some of the Ongoing Research

Climbers and the changing positions of the Sun and Moon will induce oscillations in the ribbon. Will the oscillations cause problems for the ribbon? If so, a means of dampening the oscillation will need to be found. Perhaps future research will show how the oscillations can be used to help climbers ascend the ribbon.

Making an SE ribbon means weaving CNTs into a ribbon. What's the longest length of CNT that can be manufactured? How does weaving them into a one-meter-wide and 22,000-mile-long (or greater) ribbon affect the ultimate strength of the ribbon? What happens to the SE ribbon as CNT fibers within it break? Will atomic oxygen in space attack the ribbon? Will climbers damage the ribbon every time they climb it? If the ribbon cannot be made from 22,000-mile-long CNTs, then a method of combining panels must be developed.

Our country had the foresight to create the National Nanotechnology Institute (NNI). With its $990 million budget, the Institute encourages the development of nanotechnology and studies its potential health effects. While the primary focus of the NNI is not the SE, spin-offs will make their way into the design of the SE.

On a level more accessible to the amateur, the Spaceward Foundation (**www.spaceward.org**) is initiating a climber competition. Amateurs and professionals alike have the opportunity to try their hand at designing a small-scale climber. The 2005 competition — for which awards of up to $50,000 are offered — is for climbers that can climb faster than one meter per second for at least 100 feet carrying 100 pounds of payload and using a 10 kW light source for power.

You'll find information on the climber and ribbon competitions at **www.elevator2010.org/site/competition.html** Perhaps those of us in robotics clubs should encourage our own, less demanding, climber competitions.

Arthur C. Clarke said we would see an SE 50 years after people stopped laughing at the idea. With the discovery of CNTs and their incredibly high strengths, people have finally stopped laughing. Perhaps we'll see the first SE in the lifetime of most *Nuts & Volts* readers.

Final Notes

One of the many issues to resolve is how to safely traverse Earth's Van Allen Radiation Belts. I'd like to make a few comments on this topic and lay to rest one of the silliest statements made by the Moon Hoax crowd.

All moving electrical charges produce, and are affected by, magnetic fields. Earth's intrinsic magnetic field, therefore, traps moving charged particles emitted by the Sun and other sources in the depths of space. Charged particles spiral around Earth's magnetic field lines as they travel towards Earth's poles. As they approach Earth, the magnetic field lines get closer together, increasing the strength of the local field.

A charged particle will approach Earth's poles until the magnetic field becomes strong enough to bounce it back like a mirror. If a charged particle has enough energy, it can slam into Earth's atmosphere. At that point, it gives up its energy and is absorbed within the atmosphere.

With enough particles slamming into Earth's atmosphere (say, after a massive solar flare or coronal mass ejection), they will illuminate the upper atmosphere like the inside of a fluorescent light bulb — the aurora. Particles may even make it to the ground as cosmic rays.

Radiation primarily forms two belts around Earth and is centered equidistantly from Earth's magnetic poles (the magnetic poles are offset from Earth's rotational poles).

The inner belt consists primarily of energetic protons emitted by the Sun. These protons carry energies in the range of 10 to 100 MeV. The inner belt is located between 400 and 4,000 miles above Earth's surface. This belt was discovered by the first satellite launched by the United States, *Explorer 1*. The second belt is divided into two parts, an inner radiation belt of 1 MeV particles and an outer ring current of very low energy particles (50 KeV ions and electrons) (see Figure 3).

After a period of time, exposure to the Van Allen Belts without protective shielding is fatal. The Apollo astronauts absorbed approximately 1% of a fatal dose of radiation when they traveled over the inner belt and briefly through the outer belt. When a Moon Hoax devotee tells you that the Apollo astronauts could not have traveled through the Van Allen Radiation Belts, they're only displaying their ignorance. The radiation simply isn't that dangerous to astronauts quickly traversing the belts inside a metal spacecraft.

An SE would partially reside within the Van Allen Belts. If the SE transports people to space, then the climbers need shielding. Unfortunately, shielding usually means adding metal plates or tanks of water to the outside of the climber. The additional weight reduces the amount of cargo each climber can carry and increases the cost of each trip.

Several solutions are possible. First, climbers may be lightly shielded and make the trip through the worst parts of the belts very quickly. This doesn't prevent exposure to radiation, but it does limit it. Another possibility is that the climbers can be surrounded with powerful magnets. Some radiation will then be deflected by the climber's powerful magnetic fields. The lower the energy of the radiation, the more effective the magnetic shielding. Depending on how it's done, the radiation exposure may be as acceptable as that received during a transoceanic flight.

Alternatively, the presence of the SE may create a short circuit to the ultimate ground, Earth. Electrical current is moving electrons, and when given a short circuit to ground, they make the detour with gusto. Perhaps the SE can drain radiation out of the Van Allen Belts, thereby making radiation shielding less problematic. Of course, this will reduce the aurora displays seen on Earth. NV

References

www.xs4all.nl/~hnetten/tallest.html
www.spaceelevator.com