



The Space Elevator

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Preface

This manuscript is the result of a six-month investigation I conducted for NASA under the NASA Institute for Advanced Concepts (NIAC) program. Even though this is the final report for that study, it is really just the beginning.

The study had the same simple title as this manuscript, *The Space Elevator*. The study itself was far from simple however. The object was to investigate all aspects of the construction and operation of a space elevator, a concept that up until this time had been confined to the realm of science fiction.

The first chapter will give an overview of the space elevator concept and hopefully put everything in context. I have tried to write it such that the reader is not required to have a degree in physics to understand it. However, I am sure there are unavoidable references and notations that will be new to some readers. In these cases please check the definitions section at the back of the book for assistance (Some of these unavoidable references I have marked with a “B&D” so you will remember to look in the Basics and Definitions section). References, and there are many, will appear as small superscript numbers. These refer to the list of previous work in the back of the book that much of this study is based on.

The chapters following the first will address individual technical components of a space elevator and the challenges that come along with building and operating such a system. Unfortunately, all of the various aspects of the space elevator are interwoven. Each component is affected by the design of the others and each new challenge to the survival or operation of the space elevator has repercussions throughout the entire system. The fallout is that the technical chapters will reference each other extensively including chapters later in the manuscript. I apologize for this and hope it won't deter any interested readers. For those of you who enjoy science fiction, future technologies, and challenges I hope this technical work will spark your interest. For those of you who are pragmatic and down-to-earth, examine the details of this work and I hope it will convince you that there is an interesting development on our horizon.

I must also add that this manuscript covers only the technical aspects of building a space elevator. No political aspects are considered here.

A handwritten signature in black ink, appearing to read "Paul H. Edwards". The signature is fluid and cursive, with a large initial "P" and "E".

Acknowledgement of Support

And now as I begin the technical assault on the space elevator I would like to acknowledge the support that has made this study possible. As I mentioned already, the funding for this work came from the NIAC. This is one of the more futuristic concepts that NIAC (or any part of NASA) supports and I hope that this work will be a worthy return on their investment.

In addition I would like to thank many of my colleagues and friends for their helpful discussions especially: Bennett Link (Montana Univ.) and Carla Riedel (Montana State), Hal Bennett (Compower), Hui-Ming Cheng, Bob Fugate (Starfire Optical Observatory), Mike Edwards (Motorola), Richard Epstein (LANL), Brad Cooke (LANL), Bob Roussell-Dupre (LANL), Carl Sloan and Ted Stern (Composite Optics), Larry Mattson (TRW), Paul Emberly (Kvaerner), Eureka Scientific, Ronald Doctors, David Vaniman (LANL), Jim Distel (LANL), Mervyn Kellum Jr. (LANL) and Katherine Gluvna.

Table of contents

- Preface
- Acknowledgements
- Chapter 1: A Space Elevator?
- Chapter 2: Cable Design and Production
- Chapter 3: Spacecraft and Climber Designs
- Chapter 4: Power Beaming
- Chapter 5: Deployment
- Chapter 6: Anchor
- Chapter 7: Destinations
- Chapter 8: Safety Factor
- Chapter 9: Design Options
- Chapter 10: Challenges
 - Subsection 10.1: Lightning
 - Subsection 10.2: Meteors
 - Subsection 10.3: Low-Earth-Orbit Objects
 - Subsection 10.4: Wind
 - Subsection 10.5: Atomic Oxygen
 - Subsection 10.6: Electromagnetic Fields
 - Subsection 10.7: Radiation Damage
 - Subsection 10.8: Induced Oscillations
 - Subsection 10.9: Environmental Impact
- Chapter 11: Budget Estimates
- Chapter 12: Schedule
- Chapter 13: Future Work
- Chapter 14: Summary
- References
- Definitions and Basics

Chapter 1: A Space Elevator?

Even though the space elevator has made several appearances in science fiction, few people are familiar with the concept. In the most basic description the space elevator is a cable with one end attached to the Earth and the other end roughly 60,000 miles out in space (see figure 1.1). Standing on the Earth at the base of this “beanstalk” it would look unusual but simple, a cable attached to the ground and going straight up out of sight. Now even the youngest of you reading this manuscript will know that a rope can not simply hang in mid-air, it will fall. This is true in all of our everyday situations; however, a 60,000-mile long cable sticking up into space is not an everyday occurrence. This particular cable will hang in space, stationary and tight. The difference between why a 10-ft piece of rope will fall and a 60,000-mile long cable will not has to do with the fact that the Earth is spinning. The cable for the space elevator is long enough that the spinning of the Earth will sling it outward, keeping it tight. The 10 ft. length of rope is too short to really feel this effect. To illustrate what I mean, let me give an example. If you take a string with a ball on the end and quickly swing it around your head the string sticks straight out and the ball doesn’t fall. Now imagine that string is 60,000 miles long and your hand holding the string is the Earth. The two situations, the ball swinging around your head and the space elevator swinging around the Earth, are really quite similar. Okay, great, so we now have a cable pointing straight up into space, so what. The so what part is that it is possible to climb this cable from Earth to space, quickly, easily, and inexpensively. Travel to space and the other planets will become simple if not routine.

That all sounds straightforward doesn’t it? The 60,000 mile part may give some of you pause but trust me man has built much more massive and more complicated structures than what we will be discussing. This one is just in a particularly unique shape and location. With that said I hope you will also trust me and believe that building and using a space elevator is not nearly as simple as I have explained so far. I have left out a few details, thus the rest of this manuscript. I should also state right at the offset that this manuscript is an extension of a paper I put together that will be published any time now in *Acta Astronautica*[Edwards,2000]. The concept is the same but this study has modified many of the details found in the *Acta Astronautica* paper

The concept of a space elevator first came from an inventive Russian at the dawn of the space age [Artsutanov, 1960] but the appearances of the space elevator I enjoy most came in several science fiction books. Arthur C. Clark put together an interesting tale of the construction of the first space elevator in *Fountains of Paradise*[Clarke, 1978]. Kim Stanley-Robinson had a different and well-thought out take on how the first space elevator might arise in *Red Mars*[Stanley-Robinson,1993]. These books point out many of the basic aspects and challenges of building a space elevator and keeping it operational. I highly recommend them for their entertainment value but remember they are fiction and I wouldn’t suggest following their model for building a space elevator in reality, just follow their insights. Let me explain.



Fig. 1.1: Scale drawing of the Earth with a space elevator.

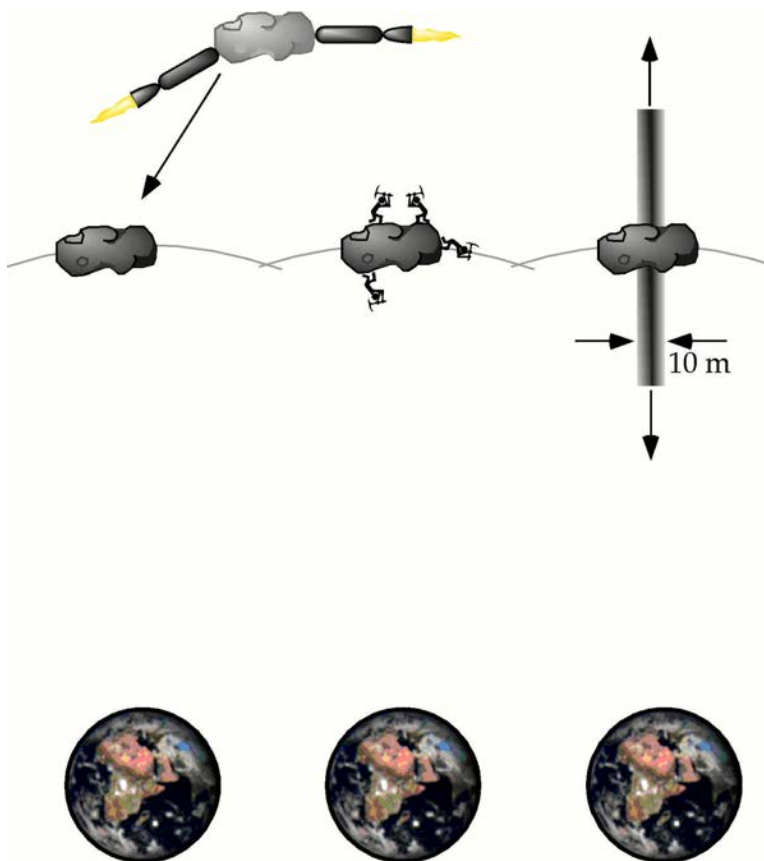


Fig. 1.2: Illustration of how a space elevator is constructed in several science fiction books. First, an asteroid is captured and placed in Earth orbit. Second, the asteroid is mined for its carbon. Third, a large cable is extruded both upward and downward until complete.

feasible at this time. I may be wrong on both of these but...well, allow me to continue.

Outside of science fiction there was some work done on the space elevator during the first decades of the space age [Isaacs, 1966; Pearson, 1975; Clarke, 1979]. These early publications worked out the physics of the space elevator and discussed some of the components such as the optimal cable design being one of a tapered cable. But even in the past few years the space elevator concept has often been discarded out-of-hand as inconceivable or at least inconceivable for the next century. The reason for the general pessimism was that no material in existence was strong enough to build the cable. Steel, Kevlar, carbon whiskers, spider web or any other material known ten years ago simply would not work. That changed in 1991 with the discovery of carbon nanotubes [Iijima, 1991]. Carbon nanotubes^{B&D} are extremely long molecular tubes of carbon where the atoms are arranged in a pattern similar to what is found in geodesic domes. Theoretically they are stronger per kilogram than any other material by a factor of 40. As an example, a fiber made of carbon nanotubes 1/8" (3mm) in diameter could support 45 tons (41,000 kg). For building the space elevator this strength is critically important. Using a material other than carbon nanotubes it was estimated that it would take 750,000 shuttles to place the space elevator in orbit [Pearson, 1975], not really something most people would seriously

In both of the books I just cited a natural object, asteroid or moon, is moved into a proper orbit and mined for its carbon. This carbon is then used to build a very strong, very large cable extending both upward and downward (figure 1.2). This was and still is a reasonable conceptual suggestion for one possible construction method [Smitherman, 2000]. However, I would consider this method as too expensive and too difficult to be a viable option outside of science fiction. The capture and movement of an asteroid, though not impossible, would be extremely challenging. In addition, the operations that would be required at very high Earth orbit (mining and cable fabrication) are also beyond what I would consider economically

consider. This is the reason for the science fiction scenario of building the cable on-orbit using materials naturally existing in space. However, I believe there is a better way.

If we assume for the moment that we can get all the carbon nanotubes we need to build a space elevator, we can build it in a similar way to how difficult bridges were built in the past. In building a bridge, the first thing that was done was a small string was thrown or shot across a canyon. Then a larger string is attached to this first small string and pulled across. This process is repeated until many ropes and eventually structures are placed across the canyon. We have a serious canyon and the string is longer but the concept is the same. First, a satellite is sent up and it deploys a small “string” back down to Earth (see figure 1.3). To this string we attach a climber which ascends it to orbit. While the climber is ascending the “string” it is attaching a second string alongside the first to make it stronger. This process is repeated with progressively larger climbers until the “string” has been thickened to a cable, our space elevator. That’s a pretty simple breakdown of what we are considering, allow me to add a few more details.

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.

The initial “string” we deploy from orbit is actually a ribbon about 1 micron (0.00004 inches) thick, tapering from 5 cm (2 inches) at the Earth to 11.5 cm (4.5 inches) wide near the middle and has a total length of 55,000 miles (91,000 km). This ribbon cable and a couple large upper stage rockets will be loaded on to a handful of shuttles (7) and placed in low-Earth orbit. Once assembled in orbit the upper stage rockets will be used to take the cable up to geosynchronous orbit^{B&D} where it will be deployed. As the spacecraft deploys the cable downward the spacecraft will be moved outward to a higher orbit to keep it stationary above a point on Earth (a bit of physics we will explain later). Eventually the end of the cable will reach Earth where it will be retrieved and anchored to a movable platform. The spacecraft will deploy the remainder of the cable and drift outward to its final position as a counterweight on the end of the cable. This will complete deployment of a stable, small, initial cable under tension that can support 2724 pounds (1238 kg) before it breaks.

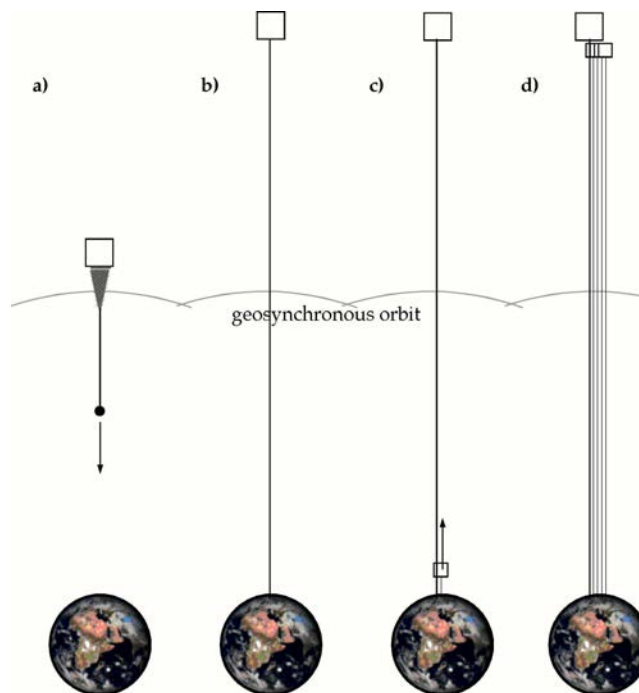


Fig 1.3: Illustration of the deployment scenario for the space elevator. A) A spacecraft is sent to geosynchronous orbit where it begins deploying a small cable. As the cable is deployed the spacecraft floats outward. B) When the end of the cable reaches Earth it is retrieved and anchored. C) Climbers are sent up the initial cable to strengthen it. D) A usable, high-capacity cable is completed.

The next stage is to increase this ribbon we just deployed to a useful size. During this stage climbers will ascend the cable and epoxy additional ribbons to the first one as they climb. At the far end of the cable the climbers themselves will become counterweights for the space elevator. One problem is how to get power to these climbers. Gasoline engines don't work well in space where there is no air and wouldn't have the required range, solar cells are too inefficient for their mass to be feasible, nuclear reactors are too heavy, an extension cord just simply wouldn't work, etc. The best option is to beam up the required energy. By using a large laser directed at solar panels on the bottom of the climber, we can efficiently send up lots of power to the climbers. This power is easily converted to electricity for running an electric motor to climb the cable.

As each climber completes its ascent the cable would be 1.5% stronger. After 207 climbers (2.3 years), the cable would be capable of supporting a 22 ton (20,000 kg) climber with a 14 ton payload (13,000 kg). This cable will have a cross sectional area forty times the initial cable I mentioned above. Payloads can be taken up the elevator to any Earth orbit or if released from the end of the cable be thrown to Venus, Mars or Jupiter. These payloads (large satellites, cargo, supplies, etc.) can be launched every four days. Additional cables of comparable capacity could be produced every 170 days using this first cable and "shipped" to other sites along the equator by dragging the lower end of the cable. In 2.8 years the capacity of any individual 22 ton (20,000 kg) cable could be built up to 1100 tons (1×10^6 kg) or roughly the size of a shuttle orbiter. And again, payloads as large as the shuttle orbiter can be sent to Earth orbit, Venus, Mars or Jupiter every four days from one of these larger elevators.

The primary use of an initial 20,000 kg capacity 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. The uses for a larger cable as discussed above would probably be for manned activities such as building and supplying a station at high Earth orbit or on Mars. All of the launch costs for putting things in orbit from the space elevator would be a small fraction of what they currently are with rockets.

Now some of you have seen concepts for space elevators that entail grand designs, large futuristic transports, several-hour travel times, large city complexes at the cable anchor and complex systems with multiple tracks on single cables. The original science fiction concepts had these and it is a wonderful scenario. The design I am proposing probably sounds small, plain and boring when compared to these. However, keep in mind that the first automobile was not a Porsche 911 and if man had refused to build any automobile unless it was a Porsche 911 horses would still be our primary mode of transportation today.

Murphy's say in all of this

We've all heard of Murphy's laws – what can go wrong, will go wrong. If we assume we can get the material to build the cable and that we can actually construct it as discussed above, are we home free? Not by a long shot. This is where Murphy has been working overtime. Getting the space elevator up is one thing, keeping it up there is something else.

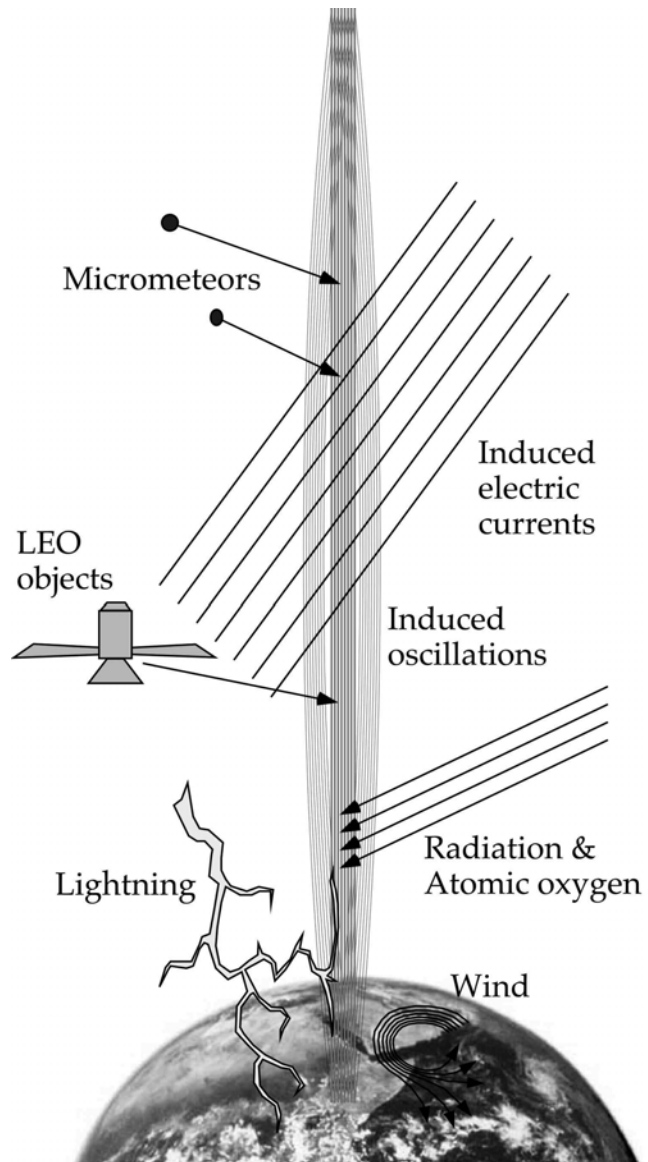
The space environment is not a pleasant one; it's more like a burning and freezing, radioactive, corrosive, shooting gallery with no air. On top of that our own environment is not that pleasant at times with things like hurricanes and lightning. There is a whole set of environmental threats the space elevator will need to survive including:

- Lightning
- Meteors

- Space debris^{B&D}
- Low-Earth-orbit^{B&D} objects
- Wind
- Atomic oxygen^{B&D}
- Electromagnetic fields^{B&D}
- Radiation
- Erosion of cable by sulfuric acid droplets in the upper atmosphere (Hieken, 2000)

Most of these are capable of destroying our space elevator on short order if we aren't careful. The first lightning storm or strong wind would destroy the bottom end of the cable, meteors would shred it before we even got the initial ribbon deployed, atomic oxygen will eat it in a month whereas a low-Earth-orbit object would hit it every 250 days. Fortunately there are solutions to each of these problems.

What we will find and discuss in the following chapters is that each of the environmental problems will drive our design. We will also find that we are actually fairly lucky, there appear to be reasonable solutions too all of our problems. As you read through the initial chapters you may see design details that are driven by problems discussed later in the manuscript. I beg your indulgence and trust that I will address these completely later in the manuscript. Let me give you a few examples. The simplest cable design is round. Our cable design is a curved ribbon. The reason for not choosing the simplest design is that the round cable would be destroyed quickly by meteors whereas the curved ribbon is more robust. Our anchor is also not a simple hook in the ground someplace in Kansas. Our anchor is located on a mobile, ocean-going platform in the Pacific 1000 miles west of the Galapagos Islands. The reason for this is severalfold. It turns out we can avoid the lightning and wind problems by locating our anchor at this specific point on Earth and by making the anchor mobile we can avoid collisions with satellites and debris in orbit. Each of the problems we may encounter including stuck climbers and a possible severed cable will force us to a specific design. In the end we find that we can solve all of the problems with a single and feasible design. We never found one killer problem that makes the design impossible.



Why would we want to build a space elevator?

Our society has changed dramatically in the last few decades from the first transistor to the internet, DVD's and supercomputer laptops, from propeller airplanes to men on the moon, from hybrid plants to mapping human DNA. Often great advances in our society take a single, seemingly small step as a catalyst to start a cascade of progress. And just as often the cascade of progress is barely imagined when that first small step is taken. The space elevator could be a catalytic step in our history. We can speculate on many of the things that will result from construction of a space elevator but the reality of it will probably be much more.

At the moment we can at best speculate on the near-term returns of a space elevator. To make a good estimate of the returns we can expect we need to know where we are now, how the situation will change if we have an operational space elevator and what new possibilities this change will cultivate. First, where we are now:

- Getting to space is very expensive: millions for the launch of a small payload to low-Earth orbit, \$400 million in launch costs to get a satellite to geosynchronous orbit and possibly trillions for a manned Mars exploration program.
- Operating in space is risky. There are few situations where repair of broken hardware is possible and believe me launch shocks do break hardware.
- Because of the limited, expensive access to space and the risk involved in space operations the satellites placed in space are also expensive and complex
- It is difficult to bring things back down from space. The only real exception to this is the space shuttle.
- Neither the government nor the public accepts failure well in the space program.

That's the current situation. The next thing we need to know is how the situation will change if we have an operational space elevator. The space elevator will be able to:

- Place heavy and fragile payloads in any Earth orbit (with a circularizing rocket) or send them to other planets.
- Deliver payloads with minimal vibration.
- Bring heavy and fragile payloads down from space.
- Deliver payloads to space at a small fraction of current costs.
- Send a payload into space or receive a payload from space every few days.
- Be used to quickly produce additional cables or increase its own capacity.
- Survive problems and failures and be repaired.

Having an operating space elevator would dramatically change our 'reality' picture of space operations as we described above. With this new set of parameters for space operations and the same economic reality we live in, we could reasonably expect the following in roughly chronological order:

- Inexpensive delivery of satellites to space at 50% to possibly 99% reduction in cost depending on the satellite and orbit. This would allow for more companies and countries to access space and benefit from that access.
- Recovery and repair of malfunctioning spacecrafts. Telecommunications companies could fix minor problems on large satellites instead of replacing the entire spacecraft.
- Large-scale commercial manufacturing in microgravity space. Higher quality materials and crystals could be manufactured allowing for improvements in everything from medicine to computer chips.

- Inexpensive global satellite systems. Global telephone and television systems would become much easier and less expensive to set-up. Local calls could be to anyplace but maybe Mars (at least initially).
- Sensitive global monitoring of the Earth and its environment with much larger and more powerful satellites. Extensive observing systems could be implemented to truly understand what we are doing to our environment.
- Large orbiting solar collectors for power generation and transmission to Earth. Power could be supplied to rural communities around the world.
- Multiple, large and inexpensive spacecraft for solar system exploration. Instead of very expensive small spacecraft taking a few photos we would have less expensive, larger spacecraft doing long-term planetary studies with videos, and a suite of every valuable scientific instrument to fully understand our neighbors.
- Orbiting observatories and interferometers many times more powerful than Hubble or any Earth-based radio telescope. Instruments many times the size of Hubble could search for and image planets around near-by stars.
- A manned space station at geosynchronous orbit for research, satellite repair, commercial manufacturing operations and prep facility for deep space and solar system exploration probes. This would be a giant leap in man's occupation of space and it could come soon after construction of the first elevator. A large station (the size of a small town) could be placed in orbit and manned with a permanent crew (not only professional astronauts) doing valuable space work on satellites and research.
- Manned Mars exploration and colonization. This is a large-scale occupation of Mars (hundreds of people) in the near future with a very affordable budget.
- Removal of man-made space debris in Earth orbit. Our space debris is causing problems for satellites and this would allow us to clean it up on a realistic budget.
- Spin-offs would include high-strength materials, better global weather monitoring, high-power lasers, and high-purity and perfect structure materials.
- Military operations would be dramatically altered with almost unlimited access to space.
- Future mining of near Earth asteroids for rare metals.
- Future vacation facilities in space. This won't be tomorrow or in the first year of operation of the space elevator but with an aggressive program our children could make reservations for a week in orbit and afford it.

These are some of the applications of the first space elevators and all but possibly the last two items would be feasible within the first fifteen years of operation including the manned exploration and colonization of Mars (see the section on destinations accessible with the space elevator). And again I believe these are feasible within the current economic environment when the commercial returns from the cable are factored in. Beyond fifteen years the best way to describe the impact of a space elevator is to say that we would have few limits in our solar system. For speculation of the possible long-term scenarios of space elevator operation I would suggest Kim-Stanley Robinson's *Red Mars/Green Mars/Blue Mars* series of science fiction novels or Arthur C. Clark's *3001*, my guess would be no better than theirs would.

Again, it is hard to grasp the magnitude of impact the space elevator would have on our society but I hope it is clear from our discussion that it would dramatically advance our society both immediately and in the distant future.

The Bottom Line

This feasibility report on the design and construction of a space elevator addresses all technical aspects of the problem from the deployment of the elevator to its survivability. This is not a definitive study or the final say but a first cut at the concept. What we have found is interesting. As we will discuss, building a space elevator will be challenging but not impossible and the initial elevator could be built for approximately \$40 billion, less than many of our larger national programs. Yet the long-term return we (humans) would receive on the construction of a space elevator is staggering, it would literally change our world.

Chapter 2: Cable Design and Production

The design of the cable entails numerous considerations many of which we cover in detail in other sections. In this section we will try to cover all the relevant components of the design and the influences that shape the design. We will begin with a background on the status of carbon nanotube progress and then address the specifics of our proposed design.

Status of Carbon Nanotube Development

In 1991 the first carbon nanotubes were made [Iijima, 1991]. These structures have promise of being the strongest material yet discovered. 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^{B&D} compared to steel at <5 GPa and Kevlar at 3.6 GPa. The density of the carbon nanotubes (1300 kg/m³) is also lower than either steel (7900 kg/m³) or Kevlar (1440 kg/m³). 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 [Pearson, 1975]) For example, based on Pearson's work and operating at the breaking point, the taper ratio required for steel would be 1.7×10^{33} , for Kevlar the ratio would be approximately 2.6×10^8 , 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 all of our discussions we have implemented a safety factor of two over the theoretical 130 GPa value. This means that at all points the cable will have twice the strength needed to support the cable below it and the suspended mass of the climber.

Carbon nanotube research is a very active area with many hundreds of papers appearing in technical journals each year. The progress in understanding the properties of carbon nanotubes and their production is encouraging. Two papers that appeared recently illustrate some of this progress.

The first paper appeared in *Applied Physics Letters* in April [Choi, 2000]. In this paper parallel, straight, clean nanotubes were grown on a nickel substrate. This in itself is not new, many researchers have now grown nanotubes by the same technique up to two millimeters long [Ren, 1998] and others have grown, with a different technique, roughly aligned nanotube ropes up to 3 cm long [Cheng, 1998]. However, Choi went a step further and characterized the growth. They clearly show an understanding of the process and demonstrate the capability to grow high-quality, densely-packed, nanotubes. They discuss the dependence of the nanotube size (multi- or single-walled) and growth rate on the initial surface preparation.

The second paper that is of interest appeared in *Science* in January [Yu, 2000a] with a follow-up of additional measurements appearing in *Physical Review Letters* in June [Yu, 2000b]. In these papers, Yu presents some of the first measured tensile strengths of nanotubes. Yu and colleagues appear to have done a thorough and well thought out experiment and got impressive results. Tensile strengths of 11 to 63 GPa were measured for individual nanotubes compared to Yu's references of theoretical tensile strengths of 300 GPa. (We used 130 GPa, Yakobson and Smalley, 1997, in all of our calculations.) The high measured tensile strength in one of the first such experiments is encouraging.

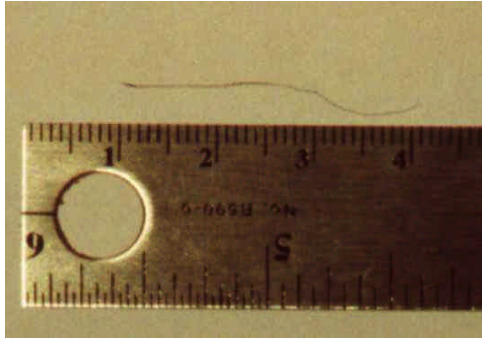


Fig. 2.1: One of our carbon nanotube bundles. The bundle is a uniform 12 microns diameter.

In our pursuit of understanding all aspects of the space elevator system we have initiated a collaboration with one of the leading nanotube researchers. The collaboration is to entail growth of long, single-walled carbon nanotubes for implementation in a space elevator cable and examining scenarios to increase the production rate of carbon nanotubes. To date we have received single-walled carbon nanotube ropes over 3 cm long (figures 2.1 and 2.2) for examination and testing. The carbon nanotube ropes we have are essentially straight, clean, 12 micron diameter single-walled carbon nanotube bundles, almost ideal for our application. These have

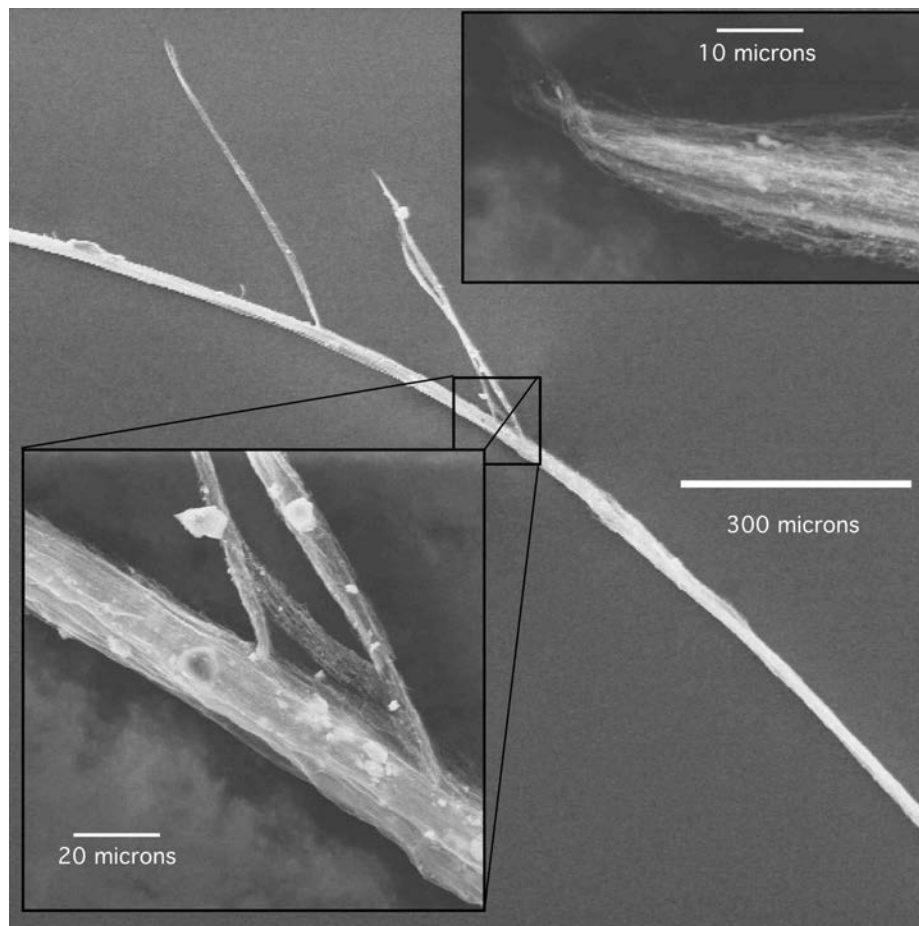


Figure 2.2: SEM images of our carbon nanotube bundle in figure 1. One end of the nanotube bundle is shown in the upper right corner. Some fraying and contaminants can be seen in the images as well as the generally aligned structure of the nanotube bundles. The individual nanotubes can not be seen in these images, they are about 1.7 nm in diameter.

been implemented in a carbon nanotube/PVC composite (Li, 2000) and found to have an estimated strength of 22 GPa. The composite itself had a lower strength (3.6 GPa) due to problems with adhesion between the PVC and nanotubes.

Another new development is the commercial sale of carbon nanotubes by Carbon Nanotechnologies Inc. (CNI). These nanotubes come in the form of a tangled mat of ropes that can be straightened through chemical methods. The individual nanotubes are thought to be several hundred nanometers in length.

Large-scale structure of the cable

The large-scale structure of the cable depends most basically on the physics of a space elevator and the tensions that the cable must support [Pearson, 1975]. The overall shape is tapered on both ends and has its largest cross-sectional area at geosynchronous orbit. The other basic design characteristic that has been known for some time is that it is best to have one cross-sectional dimension much larger than the other to reduce the damage meteors can inflict on the cable.

The length of the cable would be 144,000 km if no counterweight were used [Pearson, 1975]. With a counterweight on the upper end of the cable any length that reaches beyond geosynchronous orbit is theoretically possible. The shorter the cable the larger the counterweight mass required with it eventually reaching infinity when the cable only reaches geosynchronous. The interdependence of the total system mass, counterweight and cable length are shown in Edwards, 2000. The length of the cable should be determined by the counterweight available, cable size required, and the solar system destinations that are to be accessible from the cable (see Chapter 7: Destinations). In our proposed system we find that a cable 91,000 km long is optimal from both a construction and destination stand point. By choosing this length our cable mass to counterweight mass has a set ratio of 0.87. This ratio will define the masses of cables, spacecraft and climbers in our system.

Variations on the basic tapered design can be implemented within limits. Some modifications to our simple, uniformly thick and standard taper will help with several problems we expect to encounter. The first modification we suggest is to reduce the ratio of the width to thickness from 10,000 (10 cm by 1 micron) down to 200 (2 cm by 5 microns) at altitudes below about 7 kilometers (figure 2.3). This keeps the cross sectional area and strength of the cable the same but reduces the wind drag for the part of the cable in the Earth's atmosphere by a factor of five (see Subsection 10.4 Wind). The second modification we would recommend is increasing the width of the initial cable by a factor of 2 at altitudes between 500 and 1700 km (2. 3). This

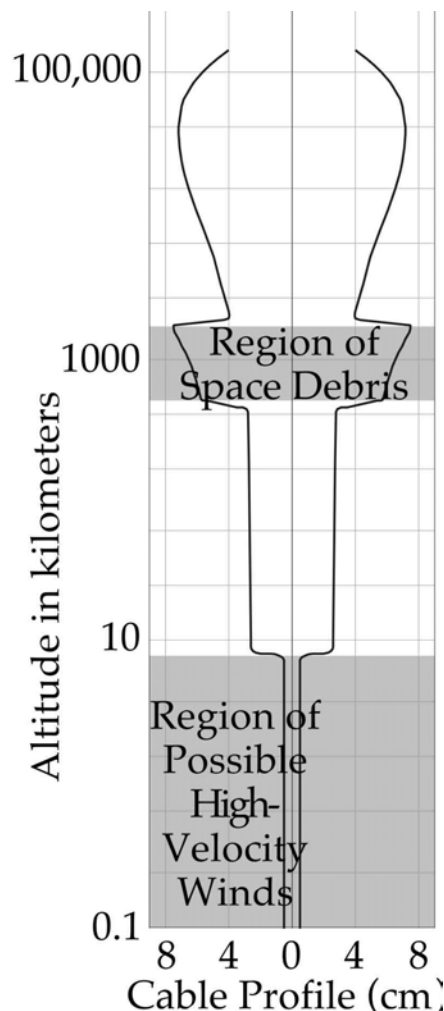


Fig. 2.3: The width profile of the proposed cable.

second modification will reduce the cable's susceptibility to meteor damage by a factor of 5 (see Subsection 10.2: Meteors) and only increase the total mass deployed by 0.65%.

Small-scale cable design

The small-scale design, microscopic up to centimeters, is also critically important to the overall success of the space elevator. The factors that will impact the small-scale design include: 1) material availability, 2) mass minimization, 3) meteor impacts, and 4) atomic oxygen. The design we are proposing for the initial cable has a width of 5 to 11.5 centimeters, a thickness of microns, alternating segments of bare nanotubes and epoxy/nanotube composite, and two thicker fibers running the length dividing the cable in thirds (figures 2.4 and 2.5).

Once carbon nanotubes of sufficient quantity and quality for our needs can be obtained the question becomes one of producing the cable. The cable we are proposing is a carbon nanotube/epoxy composite as shown in figure 2.4. The initial ribbon cable will be 5 cm wide at the base and taper to 11.5 cm at geosynchronous orbit. The thickness of this ribbon will be one micron on average. By this we mean the ribbon can be continuous as in a solid sheet one micron thick or it could be 1200 – 10 micron diameter fibers spaced across the 5 cm width.

The nanotubes making up the ribbon will be parallel and overlap in the composite sections. The filling factors of standard composite materials are 60% fibers to 40% epoxy [Rohweller, 1999]. To further reduce the mass of the epoxy component in the cable we have proposed a construction with alternating sections of epoxy composite and bare nanotubes. The bottom line is that a cable could be constructed with about 2% epoxy mass and require nanotubes of at least a centimeter in length. Figure 2.4 also shows how the cable distorts around damaged areas. In reality the distortions extend 100's of segments, only a few are shown in figure 2.4. Further consideration of the design and its performance requirements in terms of surviving meteor damage suggest that

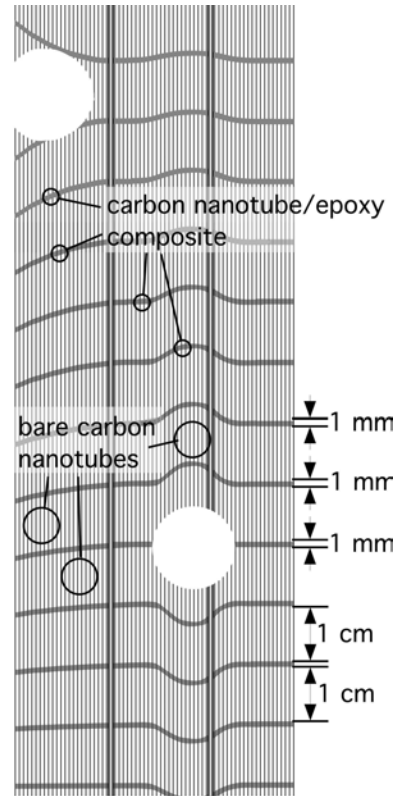


Fig. 2.4: Basic design of cable (5 cm width) with meteor damage.

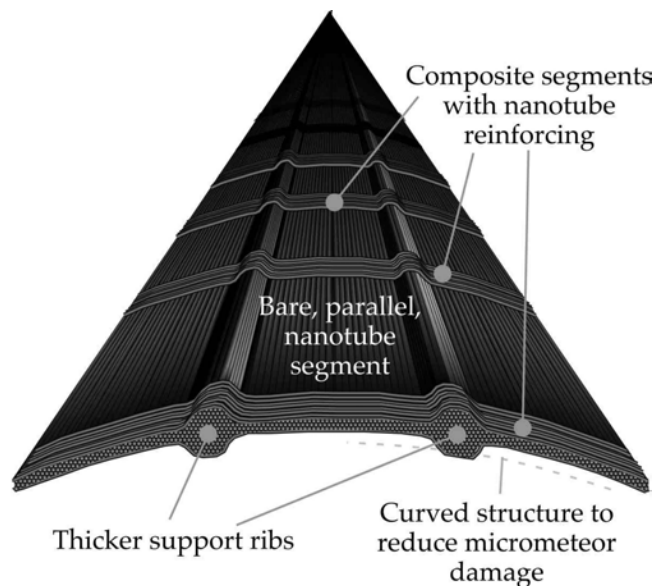


Fig. 2.5: Cut-away view of the proposed ribbon cable.

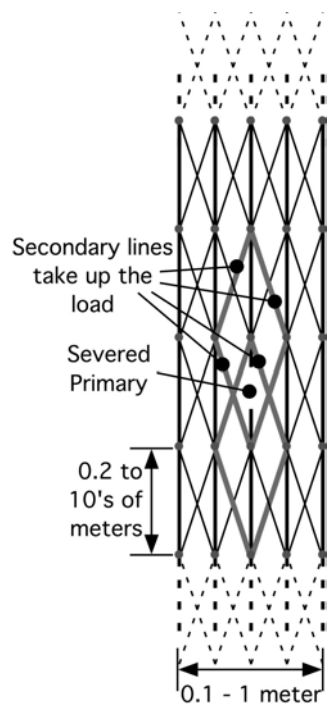


Fig. 2.6: Hoytether. Tether design by Robert Hoyt, NIAC Phase I final report.

additional strengthening of the epoxy sections with perpendicular nanotubes may be worth considering (figure 2.5). If a ribbon composed of a finite number of thicker fibers (1200 – 10 micron diameter) is used instead of the solid-sheet, idealized ribbon then the reinforcing nanotubes are probably a requirement. In the end a ribbon cable could easily have 10% (instead of our theoretical possible 2%) of its mass in epoxy and reinforcing nanotubes.

Further design aspects are driven by the affects of meteors on the cable. One aspect as discussed in the meteor and space debris section (Subsection 10.2: Meteors) pertains to curving the ribbon (figure 2.5). A curved ribbon is much less susceptible to damage by grazing incident micrometeors. A second design modification to deal more effectively with large meteors that may damage the edge of the cable is to insert two thicker support “ribs” can run the length of the cable. These thicker bundles of nanotubes would reduce the chance of a meteor hole becoming a tear where the tension stresses would be highest (figure 2.3). In redistributing the tension in damaged segments of the cable, the epoxy used will need to be strong and yet flexible to deal with meteor damage (figure 2.4). As discussed in the section on damaged cables (Subsection 10.9: Environmental Impacts) the epoxy will also need to disintegrate at a relatively low temperature to insure the cable will break-up if it were to re-enter Earth’s atmosphere. Additional studies and tests will be required before choosing the best epoxy.

Alternative cable designs

Several alternative cable designs have been suggested. One is a design by Hoyt under a study for NASA’s Institute for Advanced Concepts (figure 2.6). Hoyt’s design of a space tether consists of both straight fibers under tension running the length of the cable and crossed diagonal fibers to take up and distribute the load in the case of meteor damage. Depending on the specific design, the Hoytether could be approximately 64% heavier (Hoyt’s continuous high load tether) for the same load compared to our proposed design. In many tether applications this is not serious, in our system it would increase our system mass and launch mass by a factor of four. However, as published by Hoyt, this design may be more robust in terms of handling meteor damage and should be

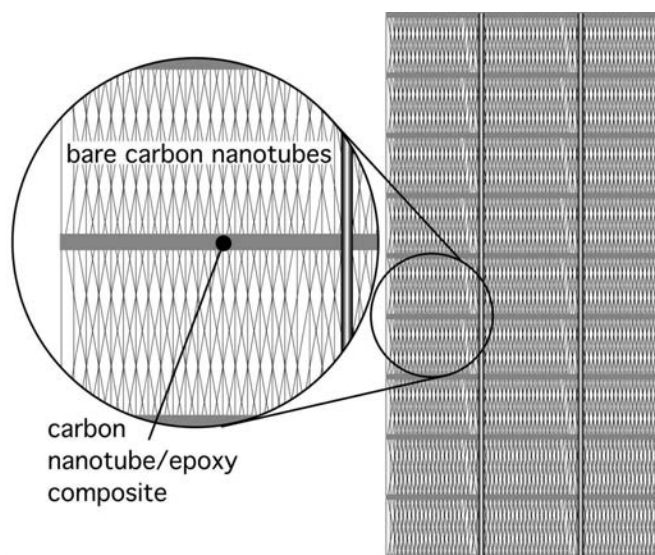


Fig. 2.7: A possible cable design based on the Hoytether. This version has all the fibers under tension (well below breaking), composite strips to connect the nanotubes and isolate the cable segments and two thicker reinforcing fibers.

seriously considered at least for possible implementation in critical sections of the cable (Epstien, 2000).

A hybrid version of our proposed cable and the Hoytether is shown in figure 2.7. We have implemented the diagonal fibers as in the Hoytether but will have these under tension. If we place these diagonal fibers at a few degrees from the axial fibers it will increase our overall cable mass by only a few percent and allow for transfer of the tension in the case of meteor damage. We have kept the nanotube/epoxy composite sections to connect the short nanotubes, keep the shape of the curved ribbon and isolate the segments of the cable. The reinforcing fibers from our proposed cable above have also been kept to reduce the chance of edge damage propagating across the cable. This design may combine the best of both our design and the Hoytether without increasing the mass dramatically.

Prior to deciding on a final cable design the problem must be examined in detail and segments of cables with various designs must be made and tested. The critical parameters include the strength to mass ratio and the resistance to damage.

Cable Production

One of the major hurdles in the space elevator program will be production of the cables. The cables are unique in their design and have high performance requirements. Let's consider our design and starting points and then determine where the major production hurdles will be. To begin with we have:

- Nanotubes are made in short lengths (see section above on carbon nanotube development status). We may need to work with lengths as short as several centimeters.
- No defects in the cable are allowed.
- The epoxy must hold the nanotubes, be strong yet flexible and burn up at several hundred degrees (see Subsection 10.9 Environmental Impact).
- The length of the finished cable is to be 91,000 km (see Chapter 7 Destinations).
- Production time for each cable must be no more than one year and it must be possible to make up to 100 in parallel (see Subsection 10.2: Meteors and Chapter 12: Schedule).

Possible useful points include:

- Nanotubes are grown aligned.
- The cable can be made in shorter lengths and then combined for faster production.

One possible scenario for producing the cable is shown in figure 2.8. If the carbon nanotubes are grown in an aligned mass it may be possible to use a weak adhesive tape to grab an aligned set of the nanotubes. These individual sets of nanotubes can be offset and aligned with each other then fed under tension into a set of treads to hold the nanotubes in position. While being held, strips of the nanotubes can be epoxied to produce the alternating composite and bare nanotube sections we require. Once epoxied the cable section is ready for spooling. If the nanotubes are grown in many centimeter lengths, they can be aligned and fed into the holding treads to be epoxied without the first adhesive pickup stage.

The difficulties will arise in insuring a good adhesion to the extremely small (1.7 nm diameter) nanotubes, elimination of all weak spots, and producing the segments fast enough. In general epoxies are cured under vacuum to produce maximum strength and adhesion. As an example let's assume that the epoxy that we use can cure in 5 minutes inside a vacuum oven. If we want to produce the cable as one segment in one year this implies that a length of 866 meters

of cable will need to be traversing through the vacuum oven at any given time. Not impossible by any means but it does need to be considered.

Either during production or after the cable is complete several tests need to be done. These tests include:

- Integrity test: Insure that the cable has no holes or weak places. This may be done using optical scanning techniques.
- Spooling: Spooling and unspooling techniques must be examined prior to production of the flight cables. It must be insured that the cable can be spooled and launched without damage and unspooled without tangling.
- Tension tests: Spot tension tests may be useful but extensive tension testing (up to 75% of breaking) to insure quality will be required.

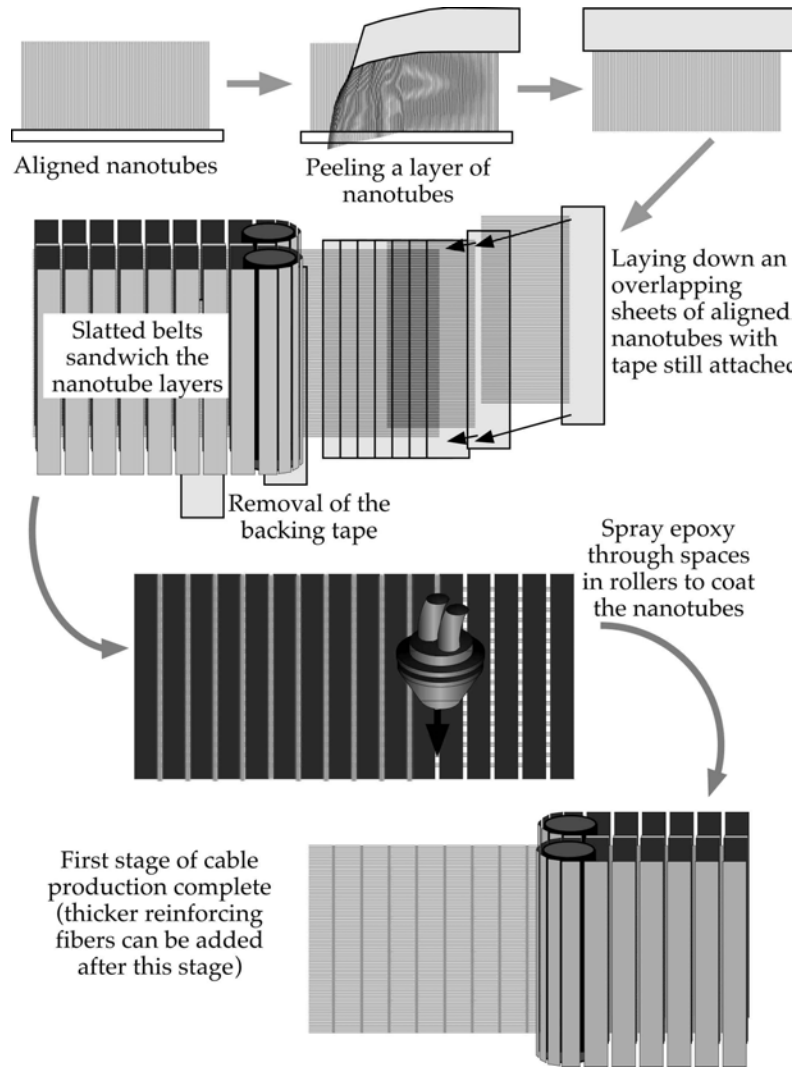


Fig. 2.8: One possible production scenario. The time consuming part of this and probably any production scheme is the epoxy curing.

Chapter 3: Spacecraft and Climber Designs

Initial Spacecraft

The spacecraft used to deploy the first cable will have some unique requirements. The spacecraft will have a large payload mass, require a specific set of mechanical actions, have a short lifetime, and minimal power, attitude control, and communications requirements. In the originally proposed scenario [Edwards, 2000] the initial spacecraft was launched to geosynchronous orbit in pieces and would autonomously assemble there. We have rethought this deployment plan and have decided to deploy the pieces to low-Earth-orbit first, assemble the pieces there with the aid of astronauts and then send the entire system to geosynchronous (see Chapter 5: Deployment). The difference is we can construct one cable with its spacecraft and send that to low-Earth-orbit instead of four spacecraft with four cables that need to be spliced on-orbit. This will save spacecraft mass and reduce the construction risk dramatically. From our deployment calculations we have determined some basic overall mass constraints (table 3.1). The masses for the subsystems can be determined by comparison with existing spacecraft.

The systems that we will need include: power, communication, attitude control, structures, cable deployment mechanisms, command, thermal and propulsion.

Power

The power required by the spacecraft is minimal. Some power will be required for attitude control and communications initially and for deployment control during most of the craft's life. Batteries or small solar panels can supply power prior to deployment. Once deployment has begun there will be excess power generated by the deployment.

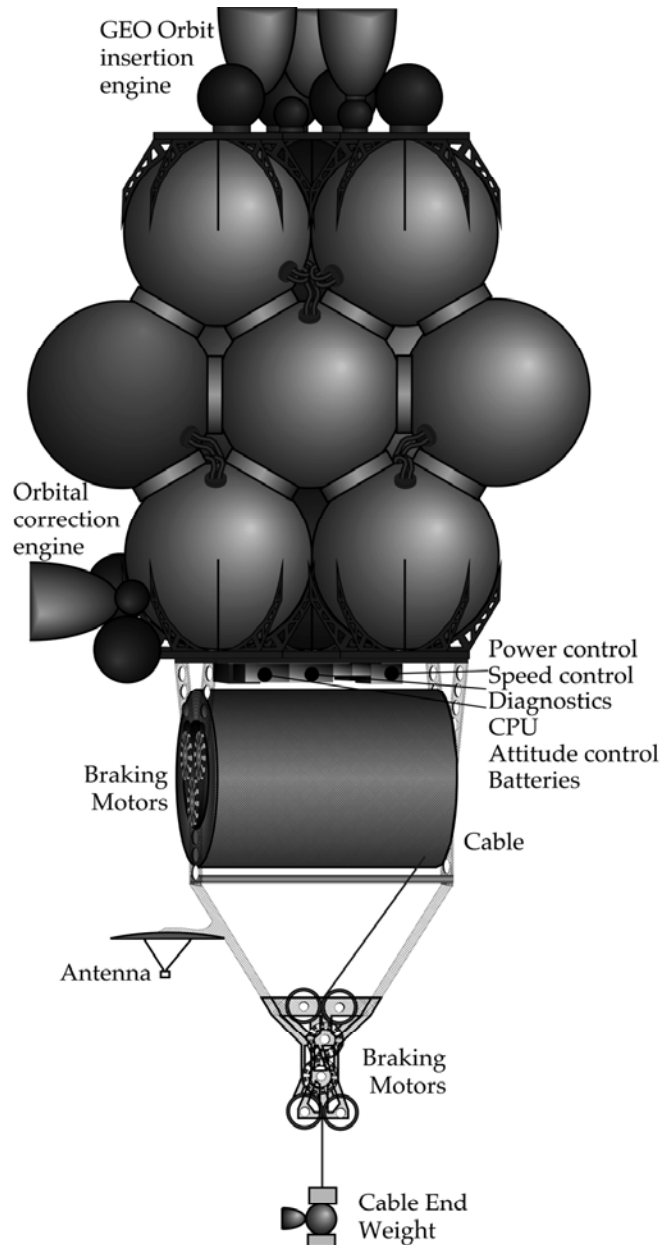


Fig. 3.1: Basic schematic of spacecraft to deploy the initial cable. Approximately to scale with each propellant tank about 2.6 meters (8 ft) in diameter.

Table 3.1: Spacecraft Mass Breakdown

	Initial SC Mass (kg)	Requirements on subsystem
Payload (cable)	19,800	
Structures	2000	Support cable mass during launch, act as spindle for deploying cable
Power	50	Provide power for the spacecraft
Attitude Control	50	Orient spacecraft relative to Nadir and other spacecraft, set spin rate
Command	15	Control deployment, cable combining process, and ascent to far end of cable
Communications	10	Housekeeping and status reports
Thermal	20	Keep electronics within operating range, control epoxy temperature
Other and contingency	850	Mechanical system for deployment control, mass on the cable end
Orbital correction prop. sys.	1620	
Orbital correction prop.	16,200	
GEO insertion prop. sys.	23,300	
GEO insertion prop.	107,000	

Communications

Communications with the craft will consist of a few commands and diagnostic downloads. Data rates of a few hundred bits per second should suffice. It is conceivable that several very wide-angle antennae may be sufficient.

Attitude Control

The attitude control will consist of pointing the spacecraft in a nadir orientation to within roughly 20 degrees and stopping any rapid rotations. Once the cable has begun to deploy, the spacecraft will be pulled into a rigid nadir orientation. Additional attitude control will be needed on the cable end weight to orient it properly and for imparting the initial angular momentum.

Spacecraft Structures

In discussions with Composite Optics (a company with experience in composite structures and systems for space) a spacecraft with 10:1 payload to structure mass is currently possible. Since our spacecraft, once in LEO, will not need to survive launch stresses, its structure can be lighter for the same payload mass as compared to current systems. Future developments and the possible use of carbon nanotubes (Since they are required for the cable, we can assume that carbon nanotube composites will be developed prior to deployment of a space elevator) will push the payload mass to structure mass ratio even higher. Our spacecraft design will have a total mass (not including the spent propulsion systems) to structure mass ratio of 10:1.

Propulsion

The propulsion systems were discussed briefly in the deployment section. Depending on how the cryogenic liquids store on-orbit and the ability to transport these systems it may turn out the two systems will actually be one large, non-cryogenic liquid-propellant system. In figure 3.1

this large propellant system is shown with twelve 2.6 meter diameter tanks (5 are not visible in figure 3.1).

Cable Deployment

In our original space elevator system proposal [Edwards, 2000] both ends of the cable were deployed at the same time and then the spacecraft moved outward to the end of the cable to act as a counterweight. However, deploying both ends of the cable from a spacecraft sitting at geosynchronous has some complexities. After further examination we believe that deploying only the lower end of the cable will work best. In this method the end of the cable is pulled downward and the spacecraft will be maintained at its geosynchronous orbit (see Chapter 5: Deployment). Eventually the end of the cable reaches Earth and the spacecraft continues to deploy more cable and floats outward (see figure 3.2). In this scenario the deployment of the cable, from a mechanical standpoint, is straightforward and has no high tension loading on the deployment mechanism inside the spacecraft.

The mechanical system for deploying the cable will need to closely control the tension and speed of the deployment and insure that no tangling or twisting occurs. In figure 3.1 the cable is shown as a single, large-diameter core spool (3m x 2.75m O.D. x 1m I.D.), however, a longer spool (6m x 2m O.D. x 1m I.D.) or multiple spool design should be investigated to reduce the chance of cable damage on launch. With deployment speeds of 200 km/hr and our proposed spool size we are talking about the spool rotating at less than 1000 RPM. This rotation rate is comparable to that of wheels on automobiles, the linear velocity is about four times as fast as commercial spooling machines.

One additional consideration is the technique for beginning the deployment. There will be no forces initially pulling the cable out so propellant may be required on the cable end weight to initiate deployment.

On the end of the cable will be a small self-contained craft. This small craft has two purposes. First, this craft is to impart a small amount of angular momentum to the cable as it is initially deployed. Once this initial angular momentum is imparted and the cable is deployed to a few hundred meters to kilometer length gravitational torques will keep the cable aligned. The second purpose of this craft is to transmit a beacon signal as the cable reaches the end of its deployment so the end of the cable can be found and retrieved on Earth.

Dissipating the Deployment Power

No power is required to deploy the cable (except for the first few kilometers) but a considerable amount of power will be generated. Depending on the deployment rate, the power that we need to dissipate could be roughly 20-40 kW for one to two weeks. This mechanical

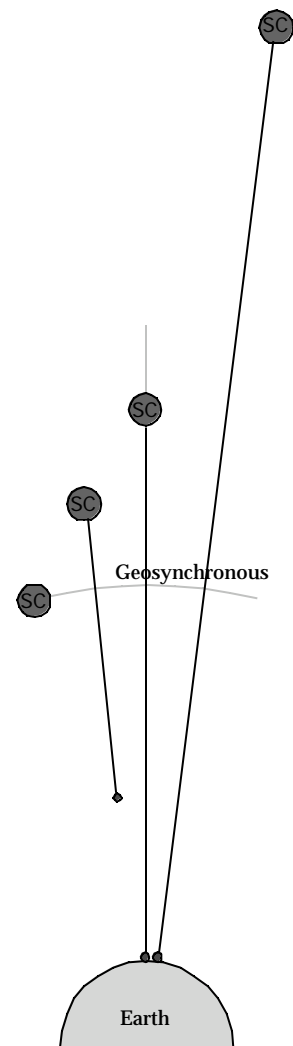


Fig. 3.2: Deployment of the initial cable. The cable is deployed downward (see discussion on imparting angular momentum to the cable) as the spacecraft is held in a geosynchronous orbit.

power can be converted to electrical with a system (DC electric motor and controller) having a mass of 15 kg per 10 kW to be dissipated (see electric motor discussion in climber design section below). Options to dispose of the excess power include:

1. Using it in an electrically driven propulsion system to maintain the synchronous orbit.
2. Converting the unwanted power to light and beaming it to where it is needed or to space
3. Converting the unwanted power to RF or other radiation and beam it away
4. Run the power through a resistor/radiator out on a boom that can handle extremely high temperatures
5. Use some of the power in TE coolers to keep the braking motor cool

Climber Design and Requirements

The climber will be designed similar to a spacecraft with some important differences. The mass, power, reliability and such are comparable to a spacecraft but the launch forces that the climber will be subjected to are minimal compared to that of a spacecraft during launch. However, unlike a spacecraft the climber will feel gravitational forces for most of its life. The climber will also have some unique mechanical requirements spacecraft generally do not encounter. The major components of the climber are the locomotion, cable deployment and power systems. There will be little ‘thinking’ to be done on the climber and minimal communications. The basic climber can be seen in figure 3.3.

From our deployment calculations we have determined a cable mass to spacecraft or climber mass for our proposed cable length and the mass capability of the initial cable. The cable to climber mass ratio is 0.87 and the total climber mass is 619 kg. This gives us 331 kg for the spacecraft and 288 kg for the cable. The cable we will be deploying on the first climber will be shorter (91,000 km vs. 117,000 km) and slightly stronger (9.7 kg vs. 8 kg) than we had originally proposed.

Cable Deployment

The primary job of the first 207 climbers will be to deploy cables as they climb and attach it to the existing cable. This will need to be done at high velocity (up to 200 km/hr) with very high reliability and in no case damage the existing cable. The tension on the cable being deployed will need to be controlled carefully to insure there is no breakage and the new segment is attached at a comparable tension to that on the existing cable. In our scenario we believe that these additional small cables should be added to the edge of the initial ribbon to widen it at least until the cable is roughly 30 centimeters wide. By widening the

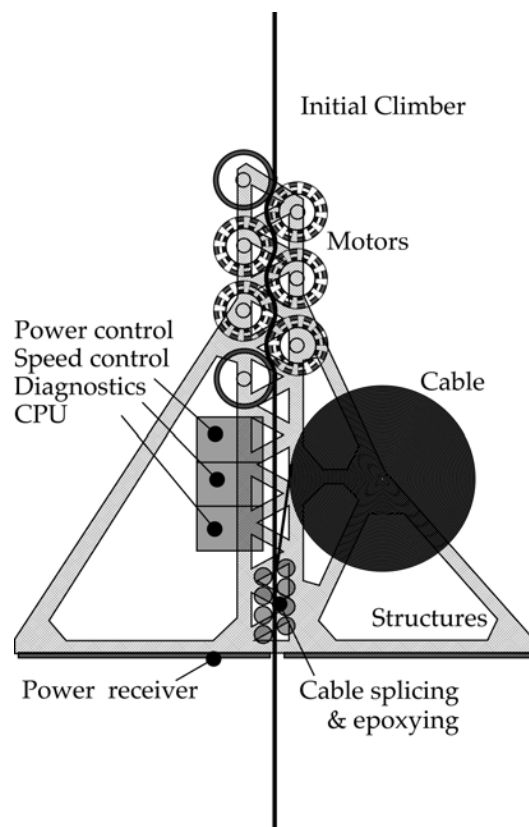


Fig. 3.3: Illustration of the various components of a climber.

cable we reduce the likelihood of catastrophic meteor damage. Once the cable reaches a 30 centimeters width then additional cables should be used to thicken the ribbon.

A second aspect of the cable splicing is the epoxy and its application. The epoxy must have some adhesion immediately such that the deployed cable will remain in contact with the existing cable and the epoxy must also cure in the environment of space (vacuum, solar radiation, temperature variations, etc.).

Motor Specifications

The locomotion system for our climber must be designed around the operational constraints of our entire program. The basic performance specs that we require include:

6. kilowatts to megawatts of mechanical power,
7. high efficiency,
8. high power to mass ratio,
9. operation in air and vacuum,
10. lifetimes of months without fail,
11. operate efficiently with torque and rpm ratios greater than 10:1
12. operate in a constant power / variable speed mode

The first six of these are pretty clear from a simple understanding of the space elevator. The last comes from the fact that our power beaming system will operate at a constant output. To best utilize the input power the climber's locomotion motor should run at a constant power. Since our load will be decreasing as the climber goes from a 1 g environment to zero g, a constant power implies that the speed of the motor will be constantly increasing during its ascent or a variable transmission is required.

Our motor study has come up with a motor design that fulfills all of the stated requirements. The motor would be based on permanent magnet brushless multipole technology to achieve a high efficiency with low mass. Cobalt-steel alloy and Neodymium-Iron-Boron magnets would be used along with a liquid cooling system and a two or three stage transmission. During most of the ascent these motors will run at greater than 96% efficiency and above 90% for most of the remainder. A 10kW motor of this design would have a mass of 14 kg, require 5 kg of control electronics and could be produced in quantity for under \$9k. A 100kW motor of this design would have a mass of 105kg, require 20kg of control electronics and could be produced in quantity for under \$50k.

Track and roller system

The track and roller system to grab the cable must be designed to hold without damaging the cable. The frictional properties of carbon nanotubes are not known. They will need to be examined before the track part of the locomotion system can be designed. In considering our cable design it is important that the track system grab the small structures of our cable uniformly. This would imply that the track in contact with the cable must be uniform and deformable on the micron scale.

This part of the system will also need to have a braking system in case power is interrupted and also a method must be available to release the track from the cable externally in case there is a malfunction (see malfunctioning climbers below). Tests and experiments will be required to optimize this part of the locomotion system.

Power System

The climber half of the power transmission system consists of photovoltaic cells for receiving the incoming laser power and a power conditioning system. There are a couple options for the photovoltaic cells and the choice is dependent on the performance of the photovoltaic cells and available lasers (see laser beaming section). The most likely scenario is to have a 3 m diameter array of photovoltaic cells located on the bottom of the climber. An alternative suggestion has been made (Hal Bennett) that the arrays could be located on the side of the climber and the power beaming stations could be fairly distant from the anchor (example: Mojave Desert). There are positive and negative aspects to this possibility and it should be examined further.

For optimal use of the motors it is best if our power system outputs voltages greater than 2500V.

In addition to receiving and utilizing the power beamed to the climber the power system must also be capable of dissipating excess energy that will be generated once the climber passes geosynchronous orbit. Depending on the velocity maintained, it will be necessary to dissipate kilowatts of power for up to several weeks. Various methods for dealing with this situation are addressed earlier in this chapter.

Thermal issues

One issue related to the climber that must be considered is thermal. If we consider a laser beaming system we will have solar cells where possibly 20% of the incident energy will be converted to heat. For our initial climber this is 17 kW. In addition we will generate 1 - 4 kW in the locomotion system. If the solar cells are isolated from the rest of the climber and exposed to space it is possible with our 3 m diameter array the panels will come into equilibrium at 400 K. (This assumes a blackbody emissivity for the panels and a 293 K ambient environment on the under side of the arrays.) This is too hot to run the photovoltaic arrays efficiently. If radiators of equal area to the arrays were added then the temperature would drop to 340 K which is much more reasonable for photovoltaic operation. This adds mass however. Since carbon composite structures are thermally conducting we may get the additional radiative cooling we need simply by having good thermal connections to our structures. This will have to be investigated further. It may also be possible to design the photovoltaic arrays to minimize the heat generated.

In addition there are thermal considerations in the motor design. Initially the motors will be operating at extremely low speeds which dramatically increases the heat production. This initial heat load affects the motor designs and can cause damage to the permanent magnets. To improve this situation we might consider a low-mass “tug” that takes the climber up the first few hundred meters until the climbers are easily pumped with the power beaming system and so the climbing motors would not need to start at zero velocity.

Structures

The support structures of the climber will require much less strength than that of a standard spacecraft since it will face no launch forces. The structure of the climber will be designed for a slowly varying load in the vertical direction with the primary structural loads existing between the cable and locomotion system. Design of the structures must consider thermal issues as well (see thermal discussion above).

Control system

The control system on the climbers will be required to monitor the speed of ascent, the tension in the cable, the splicing process and the climber location. During most of the climb the system will be in a slowly changing system with little complexity in the control required. Beyond geosynchronous, the climber will need to switch modes from a climbing mode to a braked descent. The final, and probably most important, responsibility of the climber controls is to stop the descent and lock the climber in place for use as a counterweight at the far end of the cable.

Communications

Communications like control will be minimal. The only communications that will probably be present in the climbers are low baud rate diagnostics and emergency contacts. If the climber stalls, if there is a loss of power beaming or a problem on-board then the climber should send a prompt communication.

Mass Breakdown of the Climbers

For doing what we need to do we have 331 kg of climber mass. The communications, and control system will require minimal mass (15 kg each). The structures will have less constraints on them than on a spacecraft so we can use a value that is aggressive for a spacecraft (10:1 or 58 kg). Thermal control is important in our situation but also fairly difficult to estimate a mass for at this point. For the moment, we will assign 40 kg to thermal control. If we assume we will have epoxy of the mass of 1% of the cable mass and a system to apply it including rollers we get a value for the epoxy and splicing system of roughly 40 kg. The actual control system for the power may be 15 kg leaving us 123 kg for the locomotion and solar panels. A 50 kW climbing system (7 m² of photovoltaic arrays and five 10 kW motors) requires about 96 kg (21 kg for the photovoltaic and 75 kg for the motors). The remaining 68 kg will be contingency at this point. If possible this contingency should be used for increasing the photovoltaic arrays and motors to handle 70W on the initial climber. A summary of the mass breakdown is in table 3.2.

Expandable climber design

Since we will be sending up hundreds of climbers of varying sizes it is critically important the climber is designed to be expandable. The design must allow for addition of motors, increasing the strength of the structures, larger cable spools, additional photovoltaic panels, higher heat loads, and higher power flow (see figure 3.4). The control and communications systems are the only ones that will not expand as the climbers grow.

Malfunctioning climbers

In the unfortunate case where a climber becomes stuck during its ascent there must be a method for removing the climber. One fact that complicates removal of stuck climbers is that

Table 3.2: Mass Breakdown for the First Climber

Component	Mass (kg)
Cable	288
Attitude Control	15
Command	15
Structure	52
Thermal Control	30
Epoxy and Cable Splicing	40
Power Control	30
Photovoltaic Arrays (7 m ² , 50 kW)	21
Motors (50 kW)	70
Contingency	58
TOTAL	619

the cable will probably not be able to support two climbers both at low altitudes. However, there are methods to get around this difficulty.

One option if a climber becomes stuck at a low altitude is to pull the cable down until the climber is retrieved and then allow the cable to float back out to its nominal position. In the current design of the cable the fraction of breaking strength would be pushed from 0.5 in nominal operation to 0.6 if 3000 km of the cable were reeled in to retrieve the climber. The highest stress in this situation is at the far end of the cable; the rest of the cable would be at less than 0.6 of the breaking tension.

A second option presents itself above 2600 km where the downward acceleration on the climber is less than 0.5g. In this situation a second climber without payload could be sent up to release the malfunctioning climber and carry it beyond geosynchronous orbit where it could be released. Climbers that would be sent up to retrieve a stuck climber would not have the cable load and thus have a mass of less than 40% that of a full climber. All climbers would be equipped with a release that could be accessed by a climber coming up from below.

Between 2600 km and 3000 km either of these two options are viable.

Repair climbers

In addition to the standard climbers and a rescue climber a repair climber may also be warranted. This repair climber would be sent up with short sections of cable that would be epoxied over weak sections. The climber would travel up the cable searching optically for weak sections in the cable and then place a cable patch on this section. The difficulty is that to do this efficiently the patch work would have to be done at a speed of 100 to 200 km/hr.

Repair climbers could also re-apply the coating to protect against atomic oxygen erosion. This could be a metal deposition process or possibly a metal-impregnated paint. The repair climbers would also be less massive than the cable carrying climbers and thus may be able to be sent up in between the standard climbers with minimal schedule impact.

Climbing Stage

After deploying the initial cable it will need to be strengthened and widened to make it more usable and more resilient to its environment. As the strength of the cable increases the mass of the climber and the cable it carries increase. As each climber reaches the 0.1g point (97 hours after initiating ascent) a second, slightly larger climber can be attached and sent up the cable. At this rate a 20,000 kg capacity cable can be built in 2.3 years or a 1×10^6 kg in 5.1 years. The mechanical power utilized by the climber primarily depends on the size of photovoltaic arrays and motors that can be carried. It may be possible to improve our current design and allow for more power per kilogram of climber (currently it is 50 kW for 619 kg or 81W/kg). If we can improve our power to kilogram ratio by 40% (70kW for our initial climber or 113W/kg) then we

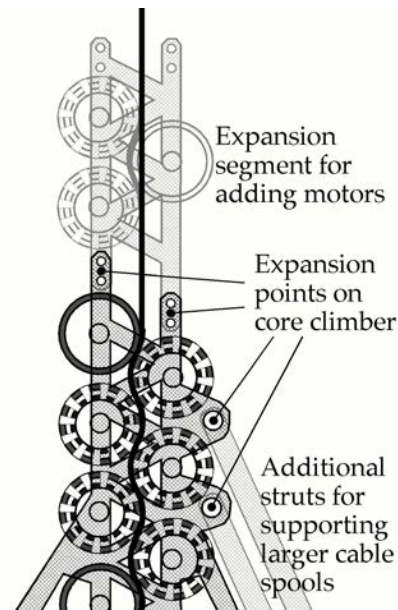


Fig. 3.4: Examples of expansion points that can be added to the climber in figure 3.3 that would allow for easy increase in climber size without a complete redesign.

can strengthen our cable to 20,000 kg capacity in 1.7 years (saving 8.5 months) or to 1×10^6 kg in 3.7 years (saving 18 months). In addition to getting a large cable on-line faster the quicker schedule also reduces the risk of cable damage.

Chapter 4: Power Beaming

Getting enough power to a climber such that it can travel from Earth to geosynchronous orbit in a reasonable amount of time is one of the technological challenges of building and using a space elevator. When considering the situation we are discussing, we find the only realistic method for getting power to the climbers is to beam it up. Alternatives that have been suggested include running power up the cable, solar or nuclear power onboard and using the cable's movement in the environment's electromagnetic field. None of these methods are feasible on further examination due to efficiency or mass considerations.

There are two scenarios we have been considering for beaming power to the climbers, microwave and laser beaming. In this section we will go through the driving constraints of both systems. In examining power beaming we found both of these techniques have been considered in the literature as possible methods for transferring power across large distances. In the laser beaming case we even found a system under construction that meets our needs.

Laser Power Beaming

First, we will examine the laser beaming system. Our preliminary examination of this scenario suggested the power beaming station may need to be located at a high-altitude sight (greater than 5 km altitude) to focus a beam tight enough to efficiently deliver power to a climber. High altitude operations are not impossible but do cause numerous difficulties and limitations. Power beaming from sea level would be much preferred. In this study we will examine this possibility.

The primary difficulty in beaming laser power up to the climbers specifically from sea level is atmospheric distortion. Atmospheric distortion will broaden the beam and reduce the power delivery efficiency.

From *The Infrared and Electro-Optical Systems Handbook: Atmospheric Propagation of Radiation*, we find a discussion of exactly the problem we are investigating. The problem of sending a laser beam from Earth to space.

The long-term beam radius can be expressed as:

$$\langle r_L^2 \rangle = r_d^2 + \frac{4L^2}{(kr_o)^2}$$

where r_o is the transverse coherence length, L is the distance from the transmitter to the receiver, D is the diameter of the transmitter, the diffraction limited spot radius is

$$r_d = \sqrt{\frac{4L^2}{(kD)^2} + \frac{D^2}{2}}$$

$$k = \frac{2\pi}{\lambda} \quad \text{and}$$

$$r_o = 1.46k^2 \sec^2 \left(\frac{L}{r_o} \right) C_n^2 \left(\frac{L}{r_o} \right) \left(1 - \frac{L}{r_o} \right)^{\frac{5}{3}} d^{-\frac{3}{5}} \quad (\text{the transverse coherence length})$$

In the case where $L \ll C$ when $C > 0$

$$r_o = 1.46k^2 \sec\left(\frac{L}{C}\right) C_n^2\left(\frac{L}{C}\right) d^{-\frac{3}{5}}$$

Following the example in the book we use the stated CLEAR I night model (this model may have some problems in our situation because the model starts at 1.2 km altitude):

$$r_o = 2.76cm \text{ for } \lambda = 0.5\mu m$$

so for a climber at 10,000 km, a 10 m transmitter and 0.5 micron wavelength we get:

$$r_d = 6m$$

then

$$\langle r_L^2 \rangle = 6^2 + \frac{4 \cdot 10,000,000 \cdot 0.0276}{\frac{2}{0.5 \times 10^{-6}}}$$

$$r_L = 58m$$

This long-term broadening can be separated into two components.

$$\langle r_L^2 \rangle = \langle r_s^2 \rangle + \langle r_c^2 \rangle$$

where $\langle r_s^2 \rangle$ is the short-term beam broadening and $\langle r_c^2 \rangle$ is the beam wander.

For the short-term beam broadening we have:

$$\langle r_s^2 \rangle = r_d^2 + \frac{4L^2}{(kr_o)^2} \left(1 - 0.62 \frac{r_o}{D}\right)^{\frac{6}{5}}$$

$$r_s = 57m$$

For beam wander we have:

$$\langle r_c^2 \rangle = 2.97 \frac{L^2}{k^2 r_o^3 D^3}$$

$$r_c = 9.3m$$

The the beam will have about 20 times the radius (400 times the area) of our originally proposed receiver. With this spot size the wander is not significant but will be significant if the

spot size is reduced. To beam up power from sea level we will require adaptive optics^{D&B} or we must live with an efficiency of $<0.25\%$. The next step is to examine adaptive optics.

From the work of Robert Fugate and others we find that adaptive optics (AO) have experimentally demonstrated a spatial resolution of 25 cm at 1000 km [Angel, 2000]. This is an order of magnitude better than our application requires at 1000 km and this system can focus the laser into the precise spot size we need at 10,000 km. With this accuracy we can place the power we need onto the 3 meter diameter solar array we have designed into the smallest climber. By the time the beam expands to fill the photovoltaic array of our smallest climber (12,000 km altitude) the power requirements of the climber are lower due to reduced downward acceleration ($\sim 0.1g$). In addition, at this altitude the next climber can start its ascent and the speed of the first climber is less critical (again reducing the power requirement).

Fugate and others have examined the problem of power beaming using lasers and find the same basic AO techniques work for power beaming that have worked for observing. They are currently planning a power beaming demonstration from Earth to a geosynchronous satellite [Lipinski, 1994]. The major problems that hinder AO applications are the lack of a bright guide star and tracking moving satellites. We have neither of these in our application. The climbers will be at known, slowly-varying positions and can be made to retroreflect part of the pump beam or emit a similar kind of tracking beacon. The only thing that has not been demonstrated is the complete beaming of a high-power laser. The primary problems that may be encountered in this next stage include thermal blooming of the atmosphere, and production of the high-power laser. In our application, thermal blooming will not be a problem with a large beam size and the power we will be using.

A complete power beaming system with 200 kW of power is the aim of Compower, a private company [Bennett, 2000] (see figure 4.1). The laser power will come from a 200 kW free-electron laser (FEL) which University of California - Berkeley will be supplying for a fixed price of \$120M. The 0.84 micron output from this laser will be directed and focused with a 12 m mirror based on the Hobby-Eberly telescope. The mirror is being modified to have more closely spaced actuators to accommodate the adaptive optics system. The system will deliver 200 kW (3ps pulses every 1 ns) into a 7 m diameter spot at geosynchronous with a 3% wallplug to laser power efficiency. The design of the laser is also readily expandable to 1MW (with possibly 30% efficiency). The current design only uses one fifth of the system (one of five wigglers) to produce the 200 kW. If all five wigglers are utilized 1 MW of laser power should be produced. This system has a five year construction schedule and its planned use is for

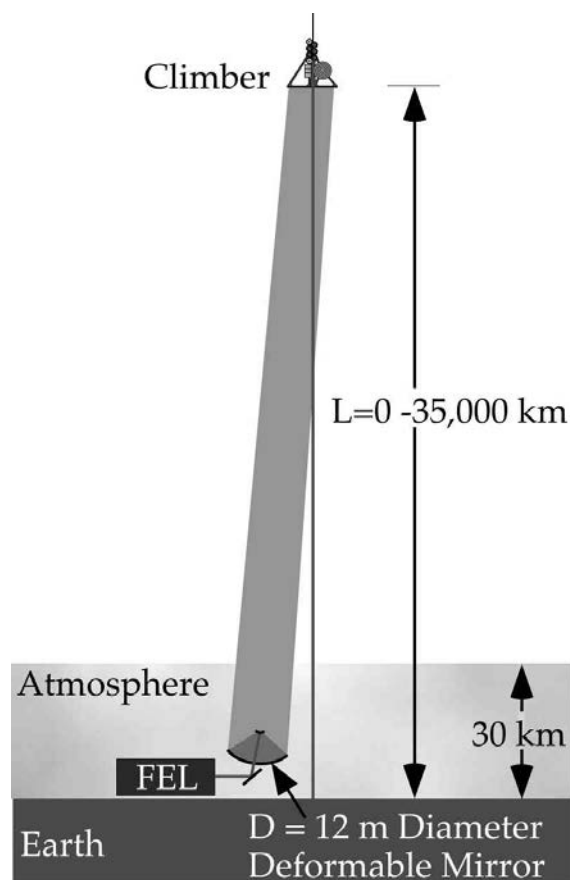


Fig. 4.1: Illustration of the laser beaming scenario.

delivering power to geostationary satellites. To expand to higher powers either the system can be redesigned or multiple identical lasers can be used with their pulses interlaced in time. In our scenario we will need 2.4 MW of power delivered to our 20,000 kg climbers so three of these systems would need to be brought on-line and their pulses interlaced. For the longer-term a 1×10^6 kg climber would require 120 MW of power delivered. We are only considering the first 20,000 kg capacity space elevator but the long-term aspects of the program must be kept in mind. It is conceivable that subsystems such as the power beaming facility or the large climbers might become the schedule driver in construction of a 1×10^6 kg capacity space elevator.

The receiver system must also be considered when examining the power beaming system. There are several photovoltaic cells that can be used as receivers and the choice depends on the laser being used, cell mass and the desired operational lifetime.

If the Compower FEL system is selected, specifically designed AlGaAs photovoltaic cells can be used with 59% conversion efficiency, 82% filling factor and 54 W/cm^2 power densities [D'Amato, 1992]. These cells would also work well with a large laser diode array as proposed by Kwon, 1997.

One additional problem that we need to address is lost transmitting time because of overcast skies. At our proposed anchor location where it would be best to also place the power

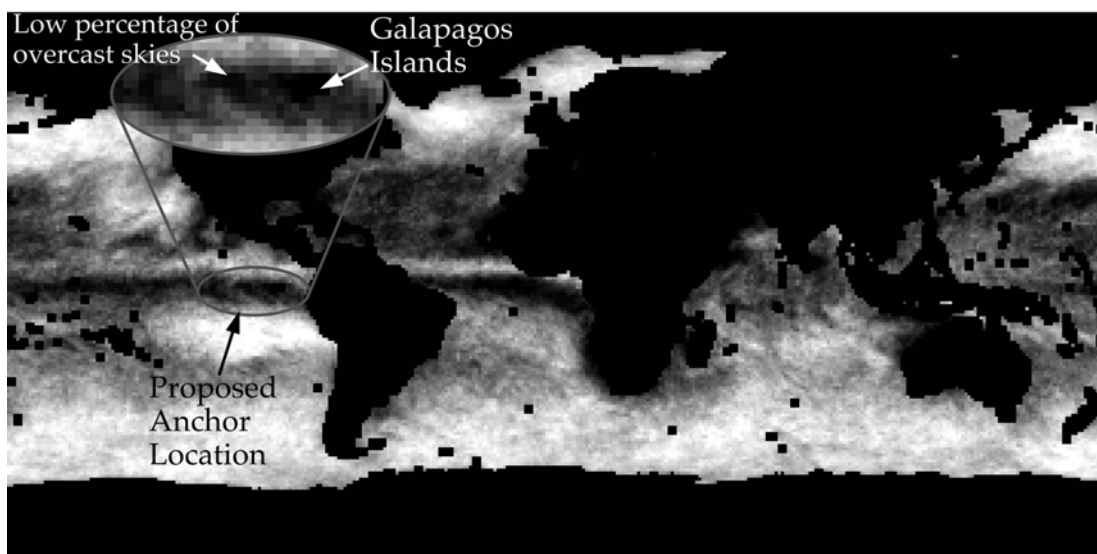


Fig. 4.2: Cloudiness frequency from satellite microwave data. The dark areas show regions of low frequency of clouds.

beaming facility, the percentage of overcast skies appears to be low (figure 4.2) but to insure continuous operations a second beaming facility located in a separate weather zone would be advisable. In our proposed situation the second beaming facility could also be located on a movable ocean platform (see Chapter 6: Anchor) roughly hundreds to thousands of kilometers from the anchor or in the mountains of Ecuador (10,000 ft altitude). An additional power beaming system in the United States (Mojave desert [Bennett, 2000]) could also be used for supplying power to climbers above 10,000 km.

Microwave Power Beaming

Several studies have been conducted on the beaming of power from space using microwaves [Brown, 1992; Glaser, 1992]. 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 [Brown, 1992: Koert, 1992]. 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 λ is the wavelength. A low-mass receiving antenna is required so we will select a baseline 3 meter diameter area ($A_r = 7\text{m}^2$, 30 kg). We also need 50 kW delivered to an altitude of 15,000 km (for the initial climber, 40 times this for the final climbers). To deliver this power to our receiver we will need a phased array transmitting antenna of at least $1 \times 10^6 \text{ m}^2$ (1 km²). Including rectenna (rectifying antenna) efficiency (50% [Koert, 1992: Koert, 1999]) and transmission efficiency (30% [Koert, 1992]) we find we will need $1.7 \times 10^5 \text{ MW}$, 792 MW, and 110 MW, going to the transmitters for 2.4 ($\lambda = 12.5 \text{ cm}$), 35 ($\lambda = 8.6 \text{ mm}$), and 94 ($\lambda = 3.2 \text{ mm}$) GHz respectively for the first climbers. This system is expandable as required by putting more power through the phased array and the received 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 35GHz for use as lightweight receivers. These rectennas have 50% total efficiency and similar results should be achievable at 94 GHz [Koert, 1999]. The mass of a the rectenna would be comparable to lightweight solar panels at 33 kg for a 50 kW receiver [Koert, 1999].

Microwaves at frequencies above 10 GHz are readily absorbed by water vapor (easily 50% absorption at 94 GHz) so careful high-altitude or dry site selection is required. If we go to the longer wavelengths where absorption is less of a problem we find the efficiency of the system drops dramatically unless a very large transmitter (1600 km²) can be built, a difficult proposition.

Power Beaming Summary

In examining the two possible systems we see that there are performance, maturity and operational differences. An overall summary of the two systems is shown in table 4.1. It is clear that at this time the laser power beaming system is the better choice of the two. The higher efficiency, smaller transmitter, and maturity of the laser beaming system are all distinct advantages over the

Table 4.1: Laser vs. Microwave Power Beaming

	Laser	Microwave
Operating wavelength	0.84 microns	3.2 mm (94 GHz)
Transmitter System	Free-Electron laser / deformable mirror	Phased array
Transmitter area	12 m diameter	1 km diameter
Receiver system	Tuned solar cells	Rectennas
Overall system efficiency	2%	0.05%
High altitude operation	Preferred	Preferred
Development level	Under Construction	Design stage

microwave system. Construction of the Compower system would eliminate any concerns on the construction or performance of the power beaming system.

Chapter 5: Deploying the Initial Cable

Angular momentum must be imparted to the cable as it is deployed to insure proper orientation. If not controlled the cable would eventually orient itself vertically due to gravitational gradient forces but either end could be pointed radially toward the Earth. Some work must be done to insure proper deployment. The most critical point is in the initial deployment, after the orientation is established gravitational gradient forces will align the cable vertically. Some consideration must also be given to damping any oscillations that may occur.

Initially we will deploy the cable with a mass on the end. If we consider a design where the mass on the end of the cable has some capabilities to accelerate itself in a specified direction we can deploy a length of cable and give it an angular momentum such that at least initially it is in the proper orientation. In this case the angular velocity will need to be

$$= 2 / (24 \ 60 \ 60) = 7.3 \times 10^{-5} \text{ s}^{-1}$$

to keep the cable nadir oriented. Or 0.46 m/s velocity for the end mass. This velocity can be imparted to our endmass with a very small, standard monopropellant system.

The next question is how do you deploy the cable further. Using gas to impart the required angular momentum just isn't feasible. A better alternative is to take advantage of the gravitational gradient torque. For this first example let's use end masses of 10 kg and an initial deployed length of 1 km. In this case the cable is massless compared to the end masses so the moment of inertia will be:

$$I = mr^2 = 10 \text{ kg} (1000 \text{ m})^2 = 1 \times 10^7 \text{ kgm}^2 \text{ for the cable with end mass.}$$

The angular momentum will be

$$p = I$$

Now if we extend the cable to 2 km the moment of inertia increases, the angular momentum will remain constant so the angular velocity decreases and the cable will begin to drift out of its proper orientation. As soon as it leaves a vertical orientation it will feel a torque due to the gravity gradient described by:

$$T_g = \frac{3\mu}{R^3} |I_z - I_y|$$

(*Space Mission Analysis and Design*, 1991)

where T_g is the gravitational torque, R is the orbital radius, I is the moment of inertia ($I_z \gg I_y$) so we will use I for I_z , μ is Earth's gravity constant ($3.9 \times 10^5 \text{ km}^3/\text{s}^2$), and θ is maximum deviation of the Z axis from vertical.

What we want to do is deploy the cable (increasing the moment of inertia) while keeping the angular velocity constant. To do this we need the spin angular momentum to increase at the proper rate. The rate at which the gravity gradient torque imparts angular momentum to our cable is dependent on the moment of inertia and angle of the cable to vertical. What this means

is that if we deploy the cable at the right velocity and at the right angle to vertical the gravitational gradient torque will keep the cable at the same angular velocity and in the same and proper orientation.

$$T_g = \frac{dp}{dt} = \frac{d(I \omega)}{dt} = \frac{d(mr^2 \omega)}{dt} = mr \frac{dr}{dt} \omega$$

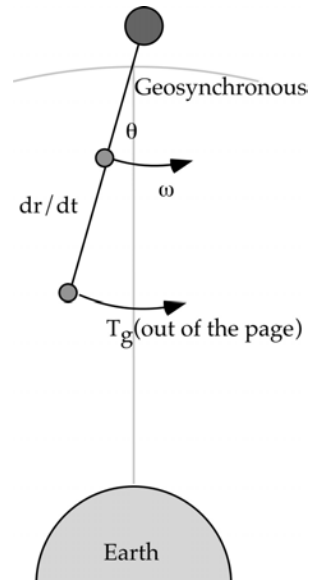
$$\frac{3\mu}{R^3} I \omega = mr \frac{dr}{dt} \omega$$

$$\frac{3\mu}{R^3} mr^2 \omega = mr \frac{dr}{dt} \omega$$

$$\frac{3\mu}{R^3} dt = \frac{dr}{r}$$

$$\frac{3\mu}{R^3} t \Big|_{r_0}^r = \ln(r) \Big|_{r_0}^r$$

$$\frac{3\mu}{R^3} t = \ln(r) - \ln(r_0)$$



This now gives us the deployment rate. The bottom line is this deployment rate is very fast. An angular deviation from vertical of 10 degree gives us a 3-day deployment rate to the Earth and a 1ns deployment to two kilometers. It implies that once the cable is orientated and deployed to a kilometer that it is stable and deployment can go at any physically conceivable rate, the gravitational gradient torque will keep the cable vertical.

One of the things that we have ignored here is the mass of the cable. During the initial deployment (the first kilometer) the mass of the cable is small compared to the endweight. Once enough cable is deployed so that the cable mass is comparable to the mass of the endweight the cable orientation will be fixed. Eventually the mass of the cable dominates the moment of inertia but the difference is a constant and appears on both sides of our equation so the deployment rate is unaffected.

The second thing that we have ignored in the calculation above is conservation of angular momentum. If we impart spin angular momentum to the deploying cable, in a closed system angular momentum has to decrease somewhere else. In our case the Earth's gravity and centrifugal acceleration are pulling on our cable. Since the cable is at a slight angle relative to vertical, part of the gravity gradient forces are converted into a force along the cable resulting in forces along the orbit instead of perpendicular to it. Due to our particular situation where the cable is comparable in size to the gravity well, we have a net force on the spacecraft and cable that reduces the orbital velocity. When this happens the cable is given spin angular momentum and the spacecraft will loose orbital angular momentum. A second fact that complicates our calculations is that as the cable is deployed different parts of it experience different gravitational acceleration. This changes our apparent mass distribution and if we want to maintain a geosynchronous orbit during deployment we must dramatically increase our orbital angular momentum. In our specific situation the geosynchronous orbit altitude for our center of mass depends on how much cable we have deployed. Suddenly we have stepped into a fairly complex situation where we must consider much more than just the cable.

Getting the system in orbit and deployment

Let's examine our deployment situation in a little more detail. First, let's say that we want our final orbit to be geosynchronous, in other words have a 24-hour orbital period. This is required for realistic use of the space elevator. Second, we will say that once the end of the cable touches Earth that no more angular momentum will be required to be supplied on-orbit. When the end of the cable is anchored all of the angular momentum that will be supplied to spin up the spacecraft and cable will come from the Earth through tension in the cable. Prior to the cable touching down we will need to supply the required orbital angular momentum with the use of rockets on the spacecraft. The spent rockets can be used as counterweights in our final system. In addition, we will need to get the cable, spacecraft and propulsion system into geosynchronous orbit. These spent rockets can also be used for counterweights if we choose. The last thing that needs to get folded in is we need to do this with reasonably conventional systems.

Let's begin by laying the groundwork.

Initially we had proposed a cable 117,000 km long as an example. If we examine this more closely we find that a shorter length may work better for us (Chapter 7:Destinations). A cable length of 91,000 km will still allow us to reach the same planets from the far end (Venus through Jupiter), be shorter and probably easier to build and allow us to have a higher mass fraction for our spacecraft. The cable mass to counterweight mass ratio for this cable length is 0.87. We will take the mass of the cable and spacecraft as variables in our calculations.

The propulsion systems and launchers we can utilize include some currently available ones and possibly ones that would be developed for this program (table 5.1).

Our complete system will be big and we can't hope to place the entire system in geosynchronous orbit directly from Earth. Accepting this then our best option will be to place the parts in LEO, assemble them there with the assistance of the space station or shuttle crew and then lift the completed system to geosynchronous. This will avoid on-orbit cable splicing since the cable can be sent up as one piece and then attached to the remaining components. It will also allow for humans to aid in the assembly whereas assembly at GEO would be autonomous. After the pieces have been assembled in LEO we will need a second stage to get us to GEO (table 5.2). Table 5.2 has information for both LEO to GEO stages and on-board propulsion systems.

With this background information we can set up our equations and solve for the masses and systems we will need. The basic scenario for getting our initial cable deployed is laid out in figure 5.2. We have selected standard shuttles to get our payload into low-Earth-orbit, a Centaur-based system to get to GEO and a bi-propellant system for imparting our required angular momentum. The shuttle was selected for several reasons. 1) The shuttle exists. No

Table 5.1: Launch Vehicles to be Considered

Vehicle	Payload to LEO (kg)	Payload to GTO (kg)	Development level	Development cost	Development time	Launch cost
Titan IVB / Centaur	21,640 (185 km)	8600	Operational	NA	NA	\$350M (2000)
Atlas V / Centaur	18,000		Operational	NA	NA	\$90M
Shuttle	24,400 (204 km)	5,900	Operational	\$10B (1977)	NA	\$245M (1988)
Shuttle-C	77,000 (400 km)		Design stage	\$3B-\$7B	3 years	Comparable to Shuttle

Table 5.2: Upper Stage propulsion Systems

Upper Stage	Dry Mass (kg)	Launch Mass (kg)	Isp	Thrust (N)	Burn time (s)	LEO to GEO	Comment
Centaur	3440	19,200	446	147,000	609	5,990	Cryogenic (~\$30m)
Star 48	189	2180	206	66,300	85	635	Solid
Ion prop			2000-6000	5e-6 – 0.5			Large dry mass
MPD*			2000	25-200			Not developed
MMH / NTO**	395	4345	325	503	25,000		In qualification testing

NOTE: The shaded information denotes areas that could be a problem for the propulsion system in our application.

*Magnetoplasmadynamic

**Information from TRW, private communication.

All other information from: *Space Mission Analysis and Design*, 1991

development is required. 2) Our system can be disassembled into components that will each fit on the shuttle. 3) The shuttle capacity allows for us to deploy the space elevator in a very reasonable number of launches. We have selected a Centaur-based upper stage because of its performance. There are some possible problems with the Centaur in our scenario. If the parts must spend much time in LEO before transfer to GEO, the cryogenic liquids in the Centaur system would begin to boil off. Depending on the scheduling for the assembly a different propellant may be required. An MMH/NTO system (TRW) has been selected for our on-board propulsion system because of its good performance and low thrust levels. The abbreviations we will use in our mass calculations are:

M: total mass

Cable: cable mass

SC: spacecraft mass

MMH: MMH/NTO system mass

MNFuel: MMH/NTO propellant mass

CenSys: Centaur system mass

CenFuel: Centaur fuel mass

L: angular momentum

w: angular velocity

Using the specifications for the existing propellant systems in table 5.2 we can extrapolate to a system that will fit our requirements. We can define the propellant to payload mass and of the LEO to GEO stage.

$$MNFuel = 10 * MMH \tag{1}$$

$$CenFuel = (19200 - 3440) / 3440 * CenSys \tag{2}$$

$$CenFuel + CenSys = 19200 / 5990 * (Cable + SC + MMH + MNFuel) \tag{3}$$

From our cable to counterweight ratio that we calculated for a 91,000 km system (see Chapter 2: Cable Design and Production) we can state

$$Cable = 0.87 * (MMH + SC + CenSys) \quad (4)$$

The other information we have relates to the angular momentum. We can calculate the angular momentum when we first get to GEO and when the cable touches the ground. This difference will have to be supplied by the MMH/NTO system. Initially

$$L_{initial} = I \omega = mr^2 \omega$$

Where the moment of inertia (I) has been expressed in its basic form as mr^2 , m will be the total mass of cable, SC, CenSys, MMH and MNFuel, r is the orbital radius from the center of the Earth (42,170 km) and ω is the angular velocity of the spacecraft as it orbits the Earth ($7.3 \times 10^{-5} \text{ s}^{-1}$).

The final angular momentum we will need to do numerically (calculate all the parts on a computer). The reason for this is that our cable is not a simple shape. To do this we simply calculate the moment of inertia for each small part of the cable and spacecraft and add them together. Since the angular velocity is the same for the entire system we can multiply the moment of inertia and the angular velocity to get the final angular momentum. The moment of inertia per kilogram of the deployed cable and spacecraft at this point will be $3.12 \times 10^{15} \text{ m}^2$ about the center of the Earth and the spin and orbital angular velocities will be $7.3 \times 10^{-5} \text{ s}^{-1}$.

$$L_{initial} = (cable + SC + MMH + MNFuel + CenSys) * 42,170,000^2 * 7.3 \times 10^{-5} \quad (5)$$

$$L_{final} = 3.12 \times 10^{15} * (cable + SC + MMH + CenSys) * 7.3 \times 10^{-5} \quad (6)$$

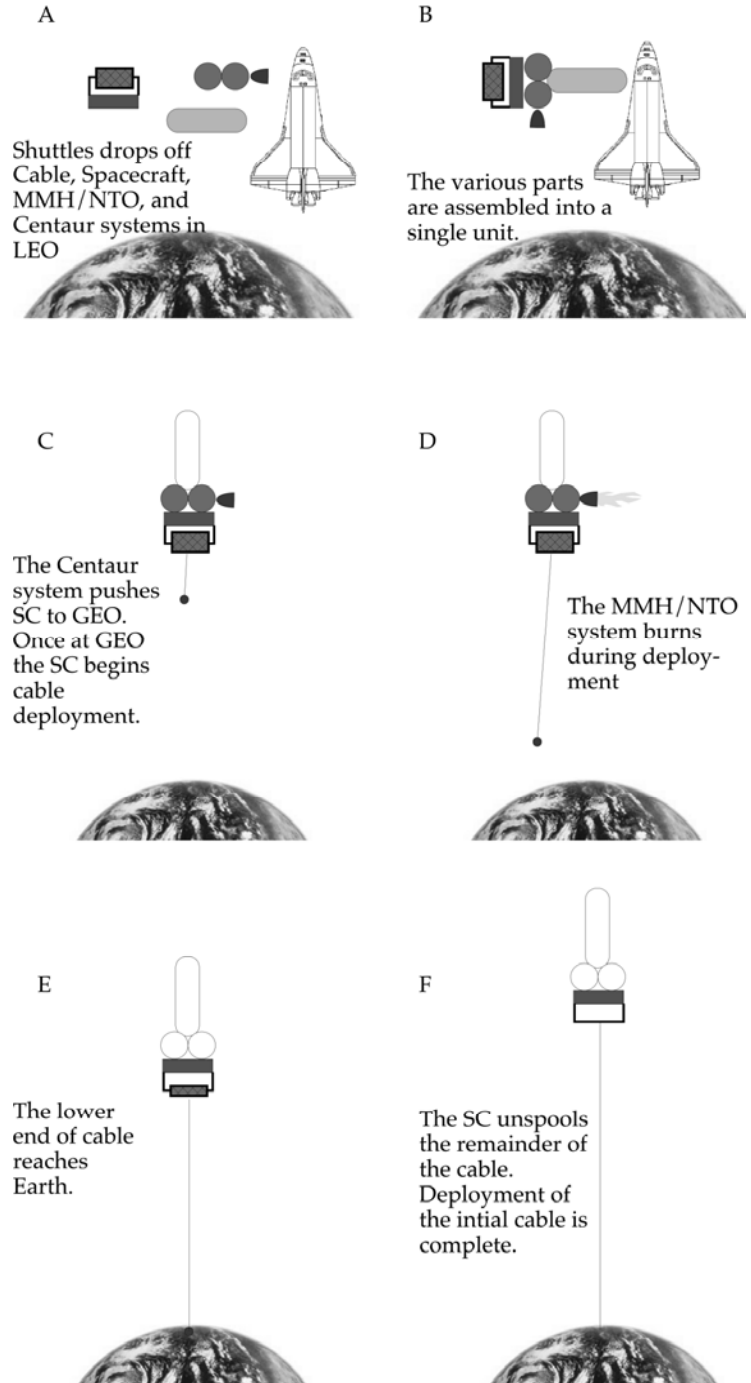


Fig. 5.2: Deployment scenario for the initial cable.

The final angular momentum we will need to do numerically (calculate all the parts on a computer). The reason for this is that our cable is not a simple shape. To do this we simply calculate the moment of inertia for each small part of the cable and spacecraft and add them together. Since the angular velocity is the same for the entire system we can multiply the moment of inertia and the angular velocity to get the final angular momentum. The moment of inertia per kilogram of the deployed cable and spacecraft at this point will be $3.12 \times 10^{15} \text{ m}^2$ about the center of the Earth and the spin and orbital angular velocities will be $7.3 \times 10^{-5} \text{ s}^{-1}$.

The difference between the initial and final angular momentum will be equal to the torque supplied by the MMH/NTO system.

$$L_{final} = L_{initial} + MNThrust * r * t$$

We can use the thrust and burn time from table 5.2 (503 N * 25,000 s / 395 kg) to give us the impulse per kilogram of MMH/NTO system mass.

$$L_{final} = L_{initial} + MMH * 503 * 25,000 / 395 * r \tag{7}$$

In this equation we will use a value for *r* that is the mean radius (50,000 km) between standard geosynchronous (42,170 km where we start) and the final position of the spacecraft when the cable touches Earth (64,070 km). This value of *r* is slightly less than the actual mean radius in our situation so it is conservative and will give us a slightly larger MMH/NTO system than we need.

We would prefer a burn time close to the time it takes to deploy the cable to Earth to minimize the forces on the spacecraft and cable so the MMH/NTO system will probably be slightly different than what we are using here for our calculations. (We will find that if we use one week the thrust of the MMH/NTO system should be about 120 N which fits well with this type of system.)

What we have laid out is a system of mass equations. We are short one equation so at this point we will arbitrarily select five shuttle launches to place our system in LEO. This gives us one more equation

$$Cable + SC + MMH + MNFuel + CenSys + CenFuel = 5 * 24,000 \tag{8}$$

To begin solving our set of equations we can use equations 2, 3, and 8 to solve for *CenSys* and *CenFuel*. Then we can solve for *MMH* and *MNFuel* using equations 1, 5, 6, 7 and 8. Finally, the *cable* and spacecraft (*SC*) masses can be obtained by using equations 4 and 8. The masses of our various components are listed in table 5.3.

It is immediately obvious we can not use these masses. The spacecraft is too small and the cable is under what we will consider our minimum size. The MMH/NTO and Centaur-type systems are reasonable, being equivalent to four and five single, standard commercial units.

Let's change a few of our parameters and try the calculation again. First we will clamp a reasonable lower limit on the spacecraft size (3000 kg). Second, we will allow for

reducing the propulsion hardware mass (either by design improvements or ejecting the mass after insertion in geosynchronous orbit). And third, we will consider using more than five shuttle launches. With this new set of conditions we find a better set of masses. The new masses using seven shuttle launches are shown in table 5.4. These masses give us a better spacecraft mass to work with, a larger

Table 5.3: First-Cut Calculated Masses for the Initial Cable and Deployment System

Cable mass	15,900 kg
Spacecraft mass	426 kg
MMH/NTO system	1160 kg
MMH/NTO propellant	11,600 kg
Centaur system	16,700 kg
Centaur fuel	76,300 kg
Total mass of payload placed in LEO	122,000 kg

cable (capacity is 620 kg with a factor of 2 safety margin), and propulsion systems that are approximately equivalent to six and seven standard commercial units. If the mass under “Reduction in propulsion system mass” in table 5.4 can be accomplished by reducing the actual mass of the propulsion systems instead of ejecting the mass once in orbit then the mass of the cable could be increased by almost half of the 5170 kg listed. This would be a 10% increase in the initial cable strength and width, which would reduce the cost, schedule and risk of the program.

Table 5.4: Modified Calculated Masses for the Initial Cable and Deployment System

Cable mass	19,800 kg
Spacecraft mass	3000 kg
MMH/NTO system	1620 kg
MMH/NTO propellant	16,200 kg
Centaur system	23,300 kg
Centaur fuel	106,900 kg
Total mass of payload placed in LEO	171,000 kg
Reduction in propulsion system mass	5170 kg

A second way to solve these same basic equations is to fix the cable and spacecraft mass, based on best estimates, and determine the required number of launch vehicles (Epstein, 2000).

There are a couple of problems with this scenario. First, launching upper stages on the shuttle is generally not permitted due to safety regulations. Thus our Centaur-based rocket may need to go up on an alternative launch vehicle, for example, an Atlas V. These launches are considerably less expensive than the shuttle, can take the required Centaurs (or at least the fuel) to low-Earth orbit and with some work (activating the second facility) four Atlas V may be able to be launched within a several week time span. A second problem has to do with the boil-off rate of Centaur’s liquid-hydrogen fuel. In their current design the Centaurs can not be left in orbit for any length of time without affecting their performance. This may mean we will need to go to a different system. Fuel systems such as the MMH/NTO have lower performance than the LO₂/LH₂ Centaurs, which means we would need an additional one or two launch vehicles to place the payload in LEO.

To launch a larger initial cable would probably require construction of the Shuttle-C^{D&B} since the cable mass we calculated above is about as large as can be placed in LEO in a single standard shuttle launch and it is best to try to avoid splicing cables on orbit. As an alternative the Shuttle-C could be developed for this program and then only three launches would be required and a 20% larger initial cable could be placed in orbit. The trade-offs are the development costs of the shuttle-C (+\$3B - \$7B), four less launches (- \$2B), 13 fewer climbers (- \$260M), possibly several months shorter deployment schedule due to fewer launches, about 6 weeks shorter climber schedule, and lower overall risk of serious meteor damage.

One additional comment should be made here concerning an alternative, yet-to-be-developed possibility. During deployment of the cable, we must keep the cable velocity in check using an electric motor as a brake. We have been designing the system on the assumption that we would dump this energy by converting it to electricity and then to light or some comparable method (see Chapter 3: Spacecraft and Climber Designs). This braking and energy dumping activity is occurring at the same time as the propulsive maneuvers to maintain the orbit. These two actions entail roughly equivalent energy transfer (due to the physics of what is happening) but one is generating and one is using the energy. If instead of dumping the excess energy from braking the cable we could use that energy in an electrically driven propulsion system (see MPD in table 5.2) we could save ourselves close to 90% of the MMH/NTO system and fuel mass. This possible design modification should be considered but at this point it is riskier than a conventional system that will work so we have not used it as our baseline.

Chapter 6: Anchor

One of the major trade-offs of the space elevator program and one of the more critical is selecting the location of the anchor. There are both political and technical aspects to selecting an anchor location. The technical selection considerations include:

- Global distribution of lightning activity (see Subsection 11.1 Lightning)
- Global distribution of cyclonic storm activity (see Subsection 11.4: Wind)
- Global distribution of smaller storms (see Chapter 4: Power Beaming)
- Requirements associated with locating a power beaming station near-by (see Chapter 4: Power Beaming)
- Available real estate to allow for mobility of the cable anchor
- Ease of construction, access and operations

When considering these criteria we come up with a short list of locations. The first possible anchor location is a floating platform located off the coast of Ecuador. The second possibility is a mountain-top location either in Ecuador or Tanzania. At this point we feel that the first option is far superior to the second.

Locating the space elevator cable anchor on a movable, ocean-going platform has numerous advantages over a land-based anchor. These include:

- Excellent mobility for moving the cable out of the path of low-Earth-orbit objects and storms
- Can be located near the equator in an area with very few lightning strikes, no cyclonic storms, few overcast days, and calm weather (~1500 km west of Galapagos islands).
- Located in international waters
- Large-scale, mobile sea platforms are tested technology (oil-drilling platforms and specifically *Sea Launch*)
- In the event of a break in the cable, the lower 1000 –2000 km of the cable would land in the ocean, above this would likely burn-up on re-entry.
- No high-altitude operational challenges such as: snow, construction on or near glaciers, difficult access by land or air, limited usable land area, and breathing difficulties due to reduced oxygen.

A good starting point for considering the various aspects of an ocean-based anchor is the *Sea Launch* program. The launch platform (*Odyssey*) for the *Sea Launch* program (figure 6.1) has the following characteristics [Emberly, 2000]:

- Refurbished oil platform
- Overall dimensions: 133m x 67m
- 46,000 tons displacement
- Power plant: 26,800 horsepower (20 MW)
- Self-propelled transit speed: 12 knots
- Cost: ~\$100M (our unofficial estimate)
- 18 months for refurbishment
- Home port: Long Beach California

Based on the *Sea Launch* program a movable, ocean-going anchor platform could be fairly straightforward. The existing platform has sufficient mass to not be affected greatly by the 20-ton capacity cable, has sufficient mobility to address our collision avoidance concerns, can have sufficient power and real estate to accommodate a power beaming system, has facilities for a substantial crew and can be built to accommodate additional needs, and has been tested in the Pacific Ocean. In the future the anchor facilities can be expanded almost indefinitely with additional floating platforms (independent or possibly interconnected).

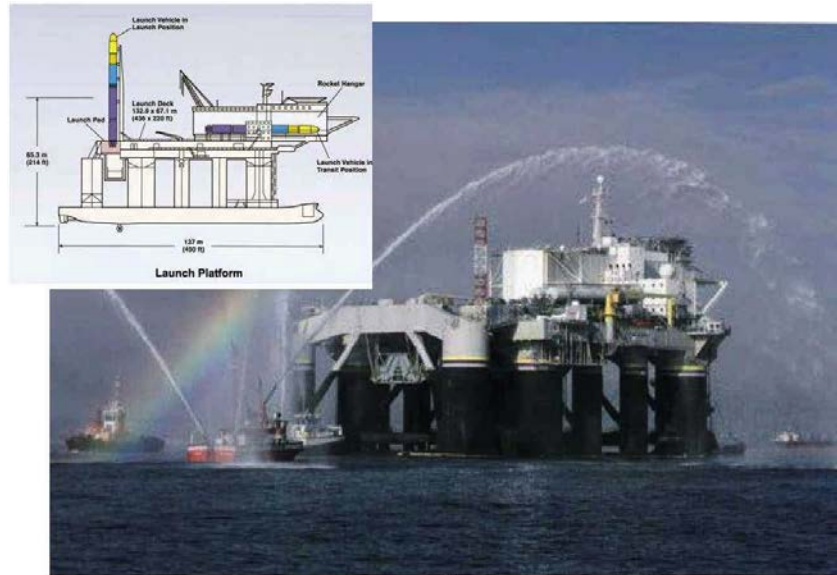


Fig. 6.1: Odyssey from the Sea Launch program.

Chapter 7: Destinations

It is easily seen the space elevator improves access to Earth orbits along its length. An additional aspect of the space elevator is that it can be used as a sling to launch payloads to more distant destinations.

To find out which solar orbits are accessible by this method we use conservation of momentum and energy.

$$mv_F R_F = mv_I R_E$$

$$\frac{1}{2} m v_F^2 - \frac{m M_{sun} G}{R_F} = \frac{1}{2} m v_I^2 - \frac{m M_{sun} G}{R_E} - \frac{m M_E G}{r_{cable}}$$

where G is the gravitational constant, M_{sun} is the mass of the sun, M_E is the mass of the Earth, m is the mass of the spacecraft, r_{cable} is the orbital altitude at the top of the cable, v_I and v_F are the velocities of the spacecraft when it leaves the cable and at the destination orbit, R_E is Earth's orbital radius and R_F is the final orbit's major or minor axis.

Rearranging and substituting we get

$$v_F^2 = \frac{v_I^2 R_E^2}{R_F^2}$$

$$\frac{v_I^2 R_E^2}{2 R_F^2} - \frac{M_{sun} G}{R_F} = \frac{v_I^2}{2} - \frac{M_{sun} G}{R_E} - \frac{M_E G}{r_{cable}}$$

$$v_I^2 R_E^2 - 2 M_{sun} G R_F = v_I^2 - \frac{2 M_{sun} G}{R_E} - \frac{2 M_E G}{r_{cable}} R_F^2$$

and we have

$$G = 6.67 \times 10^{-11} m^3 kg^{-1} s^{-2}$$

$$M_{sun} = 2.00 \times 10^{30} kg$$

$$M_{Earth} = 6.00 \times 10^{24} kg$$

$$R_{Earth} = 1.55 \times 10^{11} m$$

We can also express v_I as the velocity of the Earth around the sun plus the velocity of the end of the cable around the Earth. Thus

$$v_I = v_E \pm v_{cable}$$

where v_E equals 30,900 m/s. We can also express v_{cable} in terms of r_{cable} .

$$v_{cable} = \frac{2}{24} \frac{r_{cable}}{60 \cdot 60}$$

From the equation above we can now find what solar orbits are accessible as a function of the cable length. Both the smallest and largest accessible solar orbits are plotted in Figure 7.1.

These calculations are for orbits in Earth's equatorial plane, a rocket will be required to bring the payload back into the plane of the solar system and to circularize the orbits. Gravity assists have not been considered here. For our initial cable we will constrain our ambitions and select a cable that will allow access to Venus, Mars and Jupiter. This cable length will be 91,000 km. Once the first elevator is established, longer elevators can be constructed so the outer planets and Mercury can be reached more easily.

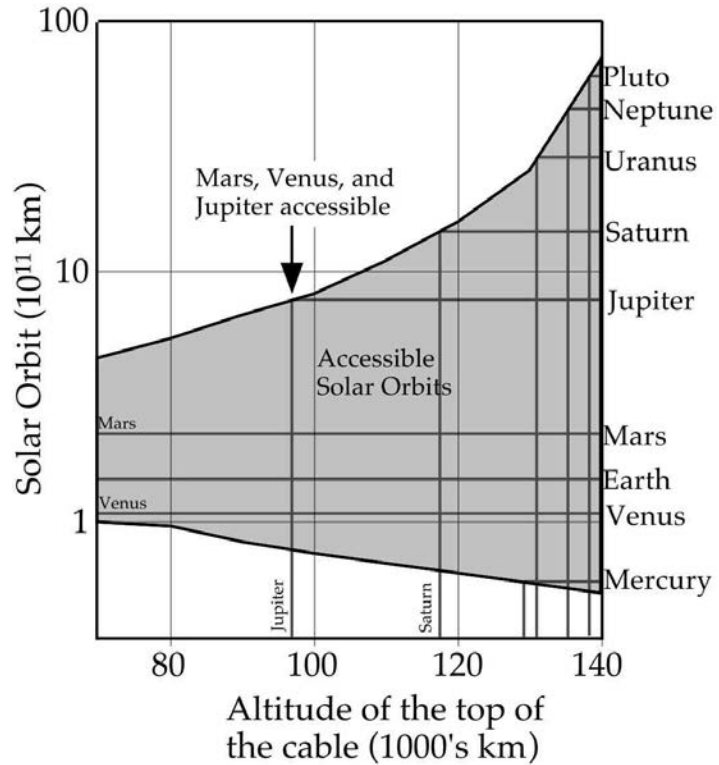


Fig. 7.1: Accessible solar orbits from the space elevator. The orbits of the planets are marked along with the cable required to access each.

Martian elevator

One additional use of the space elevator is production and delivery of a completed Mars cable (figure 7.2). The Mars cable could be produced in Earth orbit alongside an Earth elevator then released as a single unit on a trajectory to Mars. Upon reaching Mars a braking rocket or aerobraking would be required to place the cable in the proper Mars-synchronous orbit. From Mars synchronous orbit the cable would be deployed and anchored. The counterweight or a second package sent to Mars would be a space-based power beaming station. This power beaming station could utilize large solar arrays

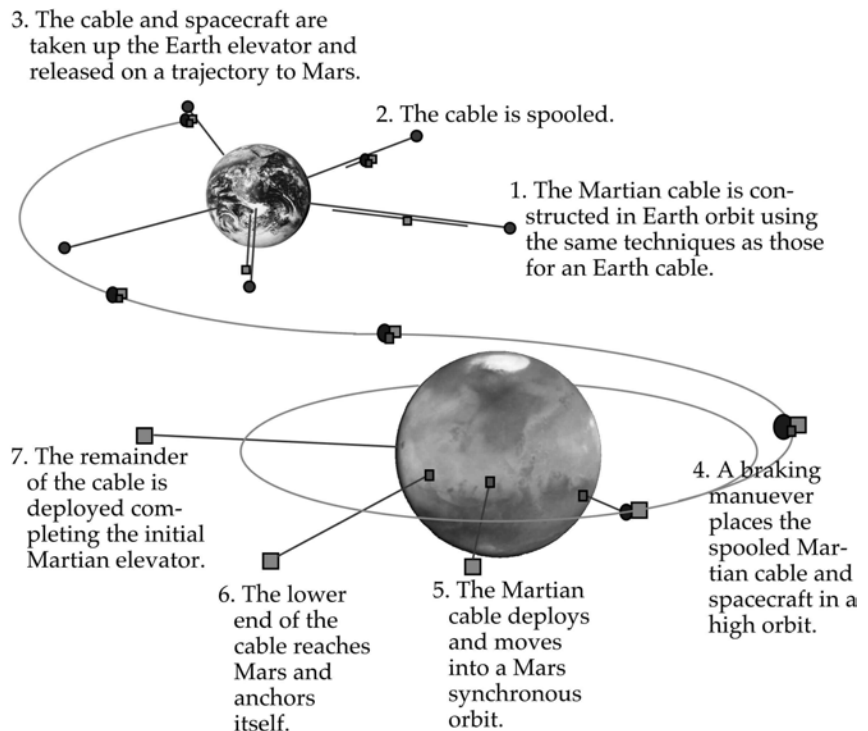


Fig. 7.2: One possible scenario for deploying a Martian elevator.

or nuclear power and a rigid mirror.

Once the Mars elevator is established transport from Earth to Mars and Mars to Earth can be done with only a plane correction rocket, attitude adjustment thrusters and climbers. For example, a climber can ascend the Mars elevator to its upper end where it releases at the proper time to acquire a trajectory to Earth. When the Mars craft approaches Earth, it attaches to the Earth elevator (the proper positioning would give an almost zero relative velocity between the cable and the craft) and descends the Earth cable to the ground.

Due to the Mars/Earth differences (lower gravity, lower synchronous orbit) the Martian cable would be roughly 1/2 the length and 1/20th the mass for the same capacity. Considering the entire cable could be built in high-Earth orbit, a 20,000 kg capacity Earth cable could be used to build and launch a 100,000 kg capacity or larger Mars elevator. The Mars elevator would have a different taper profile and not have to concern itself with lightning or man-made space debris. However, studies would have to be done to address possible Mars specific problems such as dust storms and the avoidance of Mars' moons.

Chapter 8: Safety Factor

The design of the cable for the space elevator straddles a fine line between impossibility and too fragile to survive. On one hand the cable can be designed to be strong enough to survive any problem and have orders of magnitude more strength than theoretically required. The problem is that such a cable is so massive that there is no feasible way to deploy it in a reasonable time. On the other hand a cable can be designed skirting the theoretical lower limits in strength and come down before the first climber begins its ascent. The problem is to find any middle ground that is feasible.

In the proposed system a standard safety factor of 2 was selected. This implies that the cable has twice the strength theoretically required at any point along its length. The question of a safety factor also changes as the cable is constructed. The cable is the most vulnerable at the very beginning but as it increases in size and thickness the stresses from meteors and wind diminish considerably.

The trade-off on the safety factor must be between the probability of catastrophic damage and what can be built. In figure 8.1 we can see how the taper ratio and masses of the space elevator system depend on the safety factor. The mass has a direct impact on the schedule as well. Keeping the power beaming and climber attributes the same a cable with a safety factor of 6 would take approximately 7 times as long to build as one with a safety factor of 2. In the proposed scenario this would be 16 years instead of 2.3 to put up the first 20-ton capacity cable. Improvements in the power beaming may reduce the absolute time schedule but the ratio is the same.

In the chapter on challenges we discuss the most likely causes of damage to the cable.

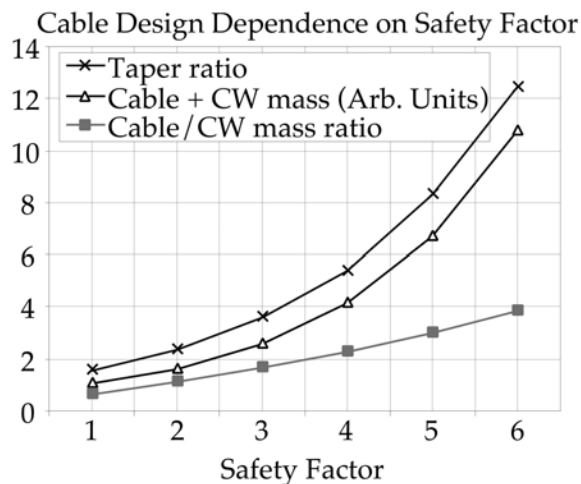


Fig. 8.1: The dependence of various cable attributes on the selected safety factor. (CW stands for counterweight)

reduce the risk of problems with much lower impact of construction.

The actual taper ratio (the primary characteristic of our defined safety factor) does not come into the risk determination for any of the possible hazards. In other words increasing our taper ratio (or safety factor) alone is not the best method to the risk of damage from meteors, atomic oxygen, wind, etc. Other modifications such as coating the cable or modifying the width and cross sectional dimensions will reduce the risk of catastrophic failure and these should be implemented.

From our understanding of the problem we find that increasing the safety factor (taper ratio) of our cable will greatly increase the construction time and costs without increasing the likelihood of our cable surviving. Other specific modifications

Chapter 9: Design Options

In the design, deployment and use of the space elevator there are various choices to be made and each of these have an impact. Below we have tried to show the impact of a broad range of possible options.

	Modification from baseline	Positive Impact	Negative Impact
1	1. Construction of Shuttle-C	1. Larger initial cable and reduced risk of meteor damage	1. Shuttle-C development costs (\$3B - \$7B)
2	1. Development of large Centaur or alternative upper stage specifically for this program to go from LEO to GEO	1. Larger initial cable and reduced risk of meteor damage 2. Reduced on-orbit operations	1. Engine development cost
3	1. Development electrically driven propulsion for orbital maintenance	1. Larger initial cable and reduced risk of meteor damage	1. Engine development cost
4	1. Increase climber's power	1. Eight months less time to deploy cable 2. Faster transport to orbit	1. Thermal issues on climber
5	1. Construction of Shuttle-C 2. Development of large Centaur or alternative upperstage 3. Increase climber's power	1. 40% larger initial cable 2. 18 months to deploy first cable 3. Eliminates risk of critical meteor damage 4. Faster transport to orbit	1. Launch vehicle development cost 2. Thermal and locomotion impacts on climber
6	1. Increase the safety factor from 2 to 4	1. Once deployed the cable is less likely to be damaged by various factors.	1. 11 years to deploy first cable 2. Higher risk of meteor damage during extended initial deployment 3. Additional climbers required for deployment

In considering the various aspects of the space elevator program, the possible risks, the impact of an operational system, and its high public visibility, we recommend implementing design option 5. As stated in the table above, this option would greatly reduce, if not eliminate, some of the major risks (meteor, wind, on-orbit operations) that we have addressed in this effort. To present an honest case, each of these options come with added costs and a more heavily load front-end funding. As with many aspects of this program, further study is warranted.

Chapter 10: Challenges

The primary influences on the space elevator design come from the environment that it must survive. The basic concept of a space elevator is straightforward but once you begin considering what will happen to it after it is deployed (and during deployment) you find that there are some design modifications that must be made. In this extended chapter we will touch on all of the major natural threats to the space elevator. The threats are in no specific order, some are extremely serious and some are of little concern but should be mentioned for completeness. With each threat we have attempted to supply a plausible solution.

Subsection 10.1: Lightning

One possible event that would destroy the elevator cable would be a lightning strike. Lightning has sufficient current and voltage potential in its arc to heat and destroy any composite that we have been considering. One could argue that the carbon nanotubes (melting point $\sim 6000^\circ$) would survive a lightning strike and that there may be a similar high-temperature epoxy that could be used for the lower section of the cable. However, we consider this a higher-risk option and believe that there may be a better solution to the problem.

The electrical properties of Earth's atmosphere are impressive as can be seen in figure 10.1.1. Potential differences of 400 kV/m can be produced with 40 C of charge stored in thunderstorm cells. The cells of potential and charge are isolated so any part of a thundercloud could be charged even if another part is shorted to ground (lightning). If we look at our cable, this means the cable will appear to be the least resistance path to ground. In other words the cable will be the path lightning will take between cloud and ground. It also means that the cable will not be able to discharge the cloud sufficiently to retard lightning, the cells could be too isolated and any individual cell could damage the cable.

Background Information

- Carbon nanotubes have a conductivity of 10^{-4} m.
- The resistance of our cable (cross sectional area $\sim 2 \text{ mm}^2$) is 50k or greater from cloud to ground (does not account for epoxy).
- Tethered balloons have been flown in thunderstorms and survived using Kevlar tethers. References to these programs have stated that the experiments were done when there was no rain. A wet tether or cable could change everything.

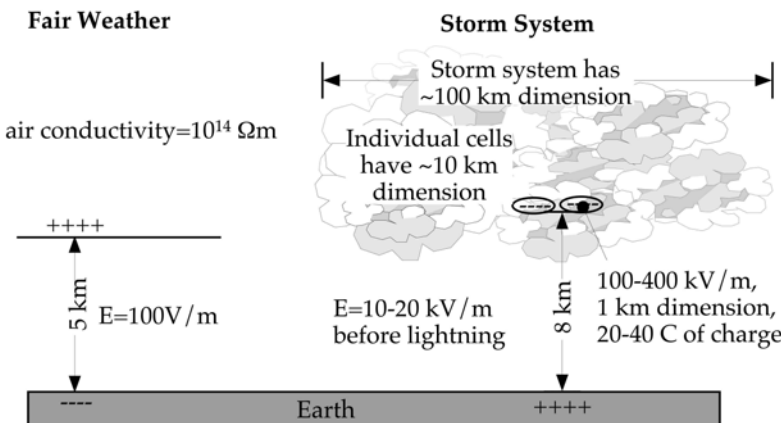


Figure 10.1.1: Illustration of the electrical properties of Earth's atmosphere

If we decide to try to make the cable with a higher resistance than air (a possibility) we might avoid a lightning strike by being the most resistive path to ground. However, rain often accompanies lightning storms and if the cable were to become wet the water may form a conductive path to ground. The lightning may take the water to ground and in the process enough of the lightning's energy may be imparted to the

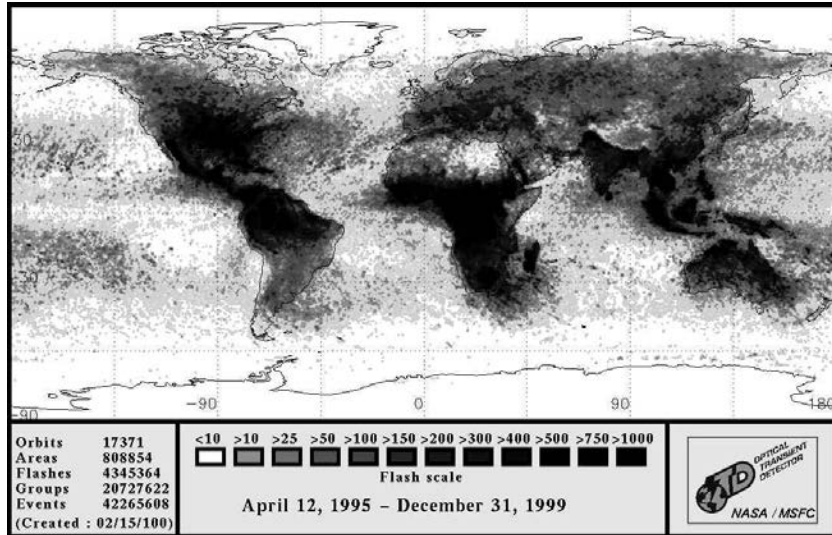


Fig. 10.1.2: Global map of lightning strikes [Christian, 1999] (flashes/km²/year) showing regions of high activity (central land masses) and regions of low activity (eastern Pacific, northern Africa, and mountain ranges including the Andes and the Himalayas).

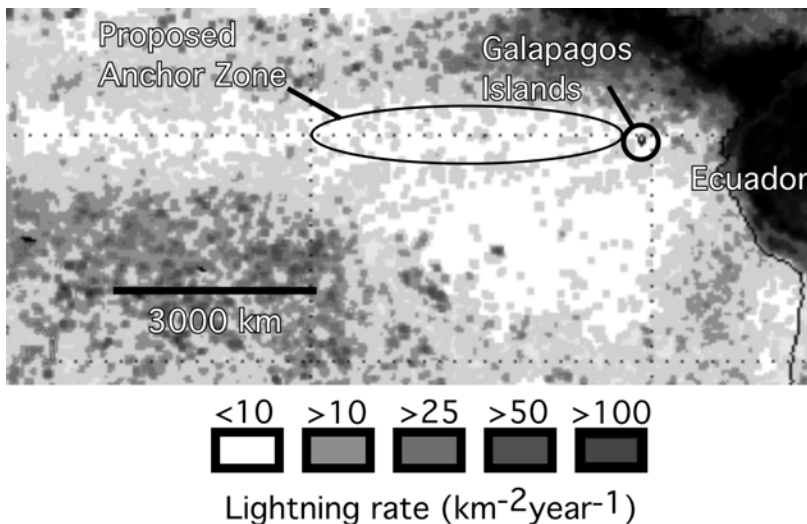


Fig. 10.1.3: Expanded view of the "lightning-free" zone in the Pacific Ocean.

cable (through the EMF field or heat or explosive pressure or ...) to destroy the cable.

Possibly the best solution to the lightning problem is to locate the cable anchor in a "lightning-free" zone like the one off Ecuador (figures 10.1.2 and 10.1.3). The anchor station would move the lower end of the cable out of the path of the few storms that do occur in these regions. In such regions less than several lightning strikes will occur over the course of a year in a 100,000 km² area. These strikes will also be concentrated in only several storms of limited spatial extent. This location and anchor movement scenario may also be required for avoiding high winds that may damage the cable.

A second alternative location for the cable anchor could be above 6 kilometers near the peak of a mountain. At least in one study it was found that there was a greatly reduced occurrence of lightning at these altitudes [Dissing, 1999].

This effect can also be seen

in lightning frequency maps (figure 10.1.2). However, there are difficulties with locating the cable anchor on a mountain peak (Chapter 6: Anchor).

Subsection 10.2: Meteors

Meteors are a serious concern for the survivability of the space elevator cable. Meteor fluxes have been measured from Earth, and their impact characteristics have been studied in-situ (LDEF) and in high velocity impact facilities. In the thick plate regime meteors will destroy an volume 50 times that of the impactor and to depths of several times the impactor’s diameter. Much of this destruction is due to the energy shock that is created in the bulk material by conversion of kinetic to thermal energy. In a thin plate scenario this changes. The shock is more intense in a solid thin sheet because the reflection off the back face combines with the initial shock. However, much of the energy also escapes out the back side of the thin plate without destroying more of the plate so the total volume destroyed in a thin plate is less than in a thick plate. In our case we have a more unique situation, we have a sheet composed of independent fibers in a very thin plane. We will see how this affects our situation. But first we will examine our environment.

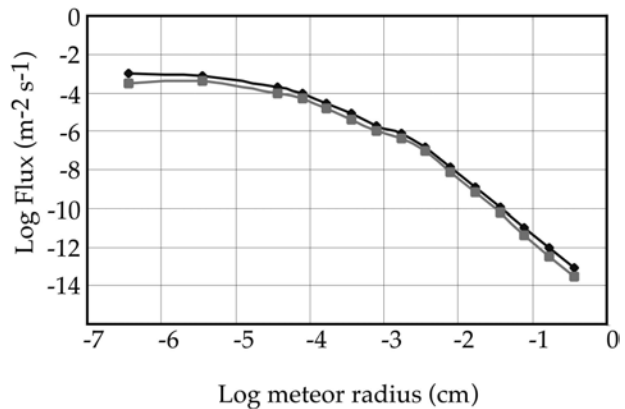


Fig. 10.2.1: Micrometeor data from Staubach, 1997. This data agrees well with that of Manning, 1959 which was used in the space elevator paper by Edwards, 2000.

Published micrometeor fluxes from several sources give roughly the same distribution (see figure 10.2.1). Below about 1 cm radius natural micrometeors dominate the population of material near Earth, above about 1 cm radius man-made space debris is the major constituent.

From the published fluxes we can calculate the impact rate we would expect and the resulting damage. If we are to assume a micrometeor will survive long enough to go straight through the cable and destroy a section (worst case), we will have catastrophic damage for large meteors at any angle of impact and for small meteors at grazing angles across the ribbon face (figures 10.2.2 and 10.2.3). For objects larger than 1 cm diameter we see the impact rate on our initial, vulnerable cable is once in several decades (figure 10.2.4). Grazing impacts by small meteors nearly parallel to the cable’s long axis will not cause catastrophic damage. The criteria we find for which meteors will damage the cable is:

$$r + \frac{r \sin(\phi)}{\tan(\theta)} \geq \frac{wf}{2}$$

where r is the radius of the meteor, w is the width of the cable, f is the fraction of cable that must be destroyed to sever it, θ is angle between the ribbon face and the incoming trajectory of the meteor and ϕ is the angle in the plane of the ribbon face between the meteor trajectory and the cable’s long axis (figures 10.2.2 and 10.2.3). Integrating over the relevant angles we can find the fraction of the meteors that can sever the cable as a function of meteor radius. Combining this with data on meteor

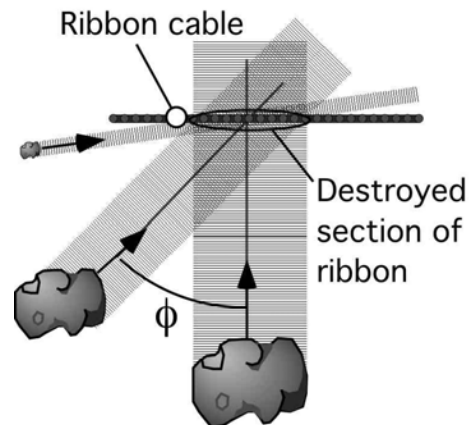


Fig. 10.2.2: Interrelation between size, angle and impact damage

fluxes (figure 10.2.1) we find how often we can expect the cable to be severed by a specific sized meteor (see figure 10.2.4). Examining figure 10.2.4 we find that the small, grazing-incident meteors will destroy our cable quickly. Initially, this does not sound good, but we need to understand the situation better to really determine how much of a problem we have. First, we assumed the meteor would pass straight through the cable destroying everything in its path. Second, we assumed the cable was perfectly flat.

When we look at our scenario, for example, we realize the 100 micron particles are coming in at angles of less than 0.25 degrees to the ribbon face and continuing straight into the cable plane (one to ten microns thick on edge) for over two centimeters without being deflected. In many cases it will run into alternating regions of bare carbon nanotubes and epoxy/nanotube composite. This implies that the cable is flat to better than 100 microns across large sections of its face. What we have is a grazing impact on a thin sheet. It turns out that studies of this situation have been done for composite sheets [Lamontage, 1999; Taylor, 1999]. These experiments used impactors with roughly the same diameter as the target thickness and examined the affect of incident angle on the penetration, damage and ejecta. What was found was that the impact and debris were deflected normal to the plane of the target and did not continue on their original path. It was also found that the damaged area and penetration depth dropped dramatically with increasing incident angles and with target thickness (the thinner the target the less area damaged). These experiments strongly argue that all impacts where the impactor and cable thickness are roughly of the same dimension (even grazing impacts) will damage no more cable area than several times that of our impactor. Now when we talk about impactors of 2 mm radius on our cable we are no longer in the same situation as in the published experiments because our impactor is now much larger than our cable is thick. In these cases further studies are required but from the data it looks likely that we will find that grazing incident impacts on our cable by meteors even several millimeters in radius will not stay in the plane of the cable and cause serious damage.

Ignoring the discussion in the previous paragraph, let's

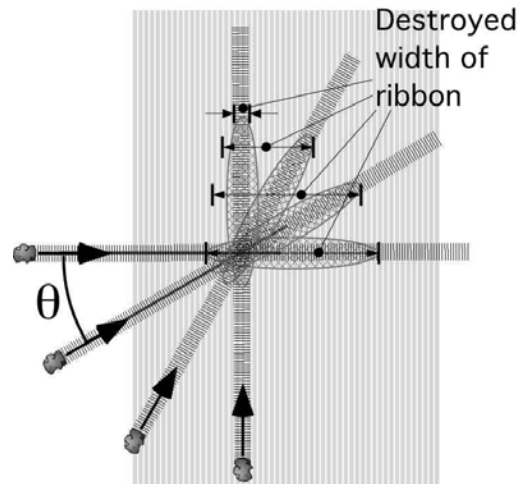


Fig. 10.2.3: Dependence of impact damage on angle of impact relative to long axis of cable. The destroyed width of ribbon cable is the critical parameter.

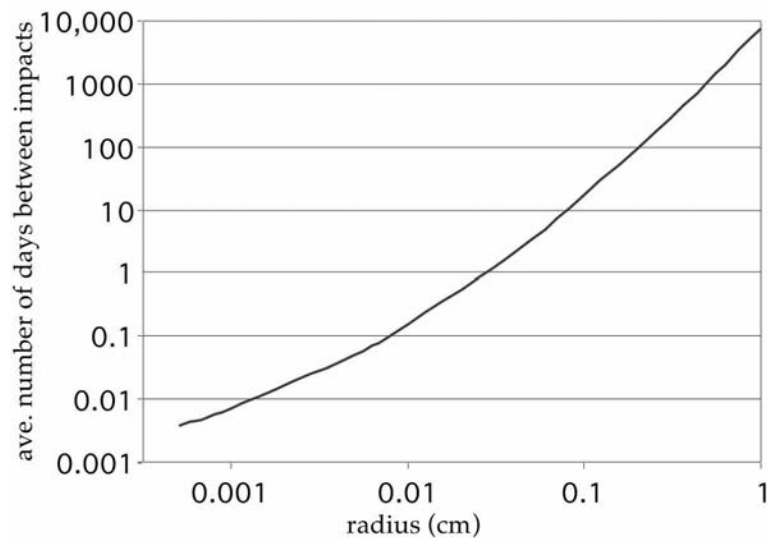


Fig. 10.2.4: Plot of the average number of days between damaging impacts on a 10 cm wide cable as a function of meteor radius.

assume we still have a problem with 2 mm radius meteors (figure 10.2.4). One way to eliminate this hazard is to give the flat face of the ribbon a curvature that has a displacement out of the plane of the ribbon of more than 8 mm over a length of 2.5 cm. This would eliminate the possibility of a 2 mm radius meteor being able to damage more than 2.5 cm of our cable (and does not substantially increase our problems for larger meteors). This curvature essentially makes a tube (radius of 19 mm) of our 10 cm wide ribbon. With a curvature of this magnitude we will eliminate the problem of small, grazing incident meteors entirely. These calculations are also only for our initial 10 cm wide ribbon. If we can place a wider initial ribbon in orbit then the meteors of concern drop in frequency linear with the width and a larger area needs to be destroyed before our cable has problems. The outcome is a flatter cable can be used. Curving the cable at the levels we are discussing has little impact elsewhere in our program.

Subsection 10.3: Low-Earth-Orbit Objects

Currently space debris larger than 10 cm diameter is tracked by U. S. Space Command. This accounts for roughly 8000 objects (satellites and space debris). An additional 100,000 objects with diameters between 1 and 10 cm are in Earth orbit. Of these objects most are in LEO (500 – 1700 km) which has the highest and most deadly relative velocity to the space elevator cable. With this density of debris we can expect the cable to be hit and possibly severed once every 250 days. One possible solution to this problem is to track all of the space debris between 1 and 10 cm diameter and move the cable out of the path of any that are on a collision course (Chapter 6:Anchor).

Haystack observatory is beginning to study and track objects in Earth orbit down to 1 cm. Optical tracking systems are also coming on-line at this time. Tracking space debris down to 1 cm has been a concern of NASA because of its affect on the space station. A study was done at Johnson Space Center [Loftus, 1993] on the construction of a new debris tracking network and came up with a design that would monitor objects down to 1 cm with 100 m accuracy using essentially current technology. This is very close to the tracking network we would need for the space elevator. An alternative system could be a set of five facilities located on the equator based on the Berkeley’s One Hectare Telescope. This would be an easily implemented and inexpensive solution.

Initially, we want to avoid all impacts on the cable from objects larger than 1 cm (this becomes less stringent as the cable grows). Based on the system proposed by Johnson Space Center the space elevator would need to avoid a piece of space debris every fourteen hours on average (see table 10.3.1). With an understanding of cable dynamics, a good computer system and the proposed anchor facility (Chapter 6: Anchor) this level of active avoidance is feasible.

Table 10.3.1: LEO Collision Avoidance of All Objects Larger than 1 cm

Tracking accuracy (m)	Time between required cable movement	Minimum size of movement required (m)
1000	1.4 hours	1000
100	14 hours	100
10	5.8 days	10
1	5.8 days	10

One additional design modification that could be implemented is to widen the initial cable slightly at orbits where the debris is highest (figure 10.3.1). The vast majority of the critical debris is located between 500 and 1700 km altitude (Interagency Report on Space Debris). If we were to design the cable to be twice as wide for these 1200 km we would reduce the risk of serious damage by roughly 30% pushing the critical meteor size up to roughly 3 cm

which is more easily tracked. The increase in the cable mass would be 0.65% including the greater cable to support this extra mass.

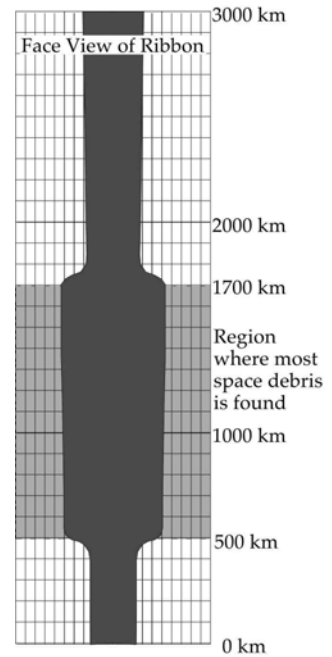


Fig. 10.3.1: Sketch of how the width of the cable may be modified to improve its survivability in regions where space debris is most prevalent.

Subsection 10.4: Wind Loading Study

Let's assume we have the initial and weakest cable deployed and a wind blowing across 1 km of its length. For a first example, we will also assume it is acceptable for the cable to be displaced such that we have a 10° deviation from a nominal position. The question is: what wind velocity will break our cable in this scenario.

The force from the wind perpendicular to the ribbon face required to break the initial and weakest cable is:

$$F = T \sin = 1240 \text{ kg } 9.8 \frac{\text{m}}{\text{s}^2} \sin(10^\circ) = 2110 \text{ N}$$

To do the calculation correctly we need to calculate the aerodynamic drag on a ribbon or set of strings or rods (the individual fibers in the ribbon) with regularly spaced plates connecting the rods (composite sections). In addition, the cable will rotate in the wind to some extent. However, we will start with a slightly simpler and worse case where the ribbon is face on to the wind. In this case, all of the fibers and composite plates see the full force of the wind. In reality there would probably be some shadowing of the wind as the ribbon turned in the wind as well as some turbulence and fluttering of the cable.

The drag of an object can be expressed as:

$$D = \frac{1}{2} C_d \rho A v^2$$

where D is the drag, ρ is the air density, A is the frontal area, v is the air velocity and C_d is the drag coefficient (1.28 for a flat plate, ~ 0.07 for a cylinder in low velocities)

For a large number of individual fibers we then have:

$$D = N \frac{1}{2} C_{cylinder} A_{fiber} v^2$$

where N is the number of fibers. For a flat plate like the composite sections we have:

$$D = \frac{1}{2} C_{plate} A_{composite} v^2$$

The total drag will be:

$$D = \frac{1}{2} \left(N C_{cylinder} A_{fiber} + C_{plate} A_{composite} \right) v^2$$

This can be solved for v :

$$v = \sqrt{\frac{2D}{(NC_{cylinder}A_{fiber} + C_{plate}A_{composite})}}$$

With the force required to break the cable from above (2110N), 1200 fibers of 10 micron diameter (one possible configuration for the first, smallest and most vulnerable cable), 5% of the length in composite and wind effective over a 1 km vertical extent we get:

$$v = 32 \frac{m}{s} = 116 \frac{km}{hr}$$

It is easily seen that almost the entire drag comes from the composite sections. The reason for this is they fill the area between the fibers making for a much larger effective area per unit length and the drag coefficient for a flat plate is almost twenty times that of the cylinder.

Looking at the wind speeds near the proposed anchor location [Chelton, 1981], (figure 10.4.1) we find the velocity distribution is actually considerably below the 32 m/s breaking velocity. However, a larger margin of safety, if we can easily get it, is always better. A second paper [Sandwell, 1984] gives a global map of the seasonal average wind speed. In the maps it can be seen the spatial distribution of high and low wind regions. The proposed anchor location (~1500 kilometers west of the Galapagos Islands) is found to have yearly low wind speeds and is in the area of very few lightning strikes.

Areas where we can further reduce the risk of damage by wind include:

1. Reducing the width to thickness ratio of the cable. (figure 10.4.2) By making the cable one fifth the width we reduce the wind load on the cable by a comparable amount and increase the critical wind velocity by sqrt(5) or from 32 m/s to 71 m/s (154 mph or a category 4 hurricane, table 10.4.1).
2. Reducing the ratio of nanotube/epoxy composite to bare nanotube length in our cable design. Since the composite sections will be creating the most drag, reducing the fraction of the cable will reduce the drag. Achieving this is dependent on the composite technology.

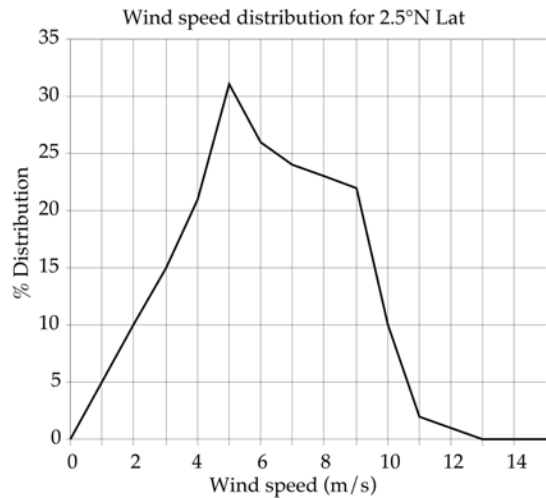


Fig. 10.4.1: Velocity distribution of wind for the proposed anchor location. This wind data is for 2.5°N ±5°.

Table 10.4.1: Storm Characteristics

Type of Storm	Category	Winds (mph)
Depression	TD	< 39
Tropical Storm	TS	39-73
Hurricane	1	74-95
Hurricane	2	96-110
Hurricane	3	111-130
Hurricane	4	131-155
Hurricane	5	>155

Location-Related Wind Considerations

If the design modifications push the critical wind velocity to roughly 154 mph then we are discussing destruction by a cyclonic storm. If we are looking at an ocean platform anchor then the storms we are concerned with are specifically category 4 hurricanes. We then have a possible solution by considering the anchor location in terms of the spatial distribution of hurricanes. Figure 10.4.3 shows the general and historical spatial locations of hurricanes. As can be seen in the global maps, hurricanes tend to exist at low latitudes in both the northern and southern hemispheres but do not occur at or cross the equator. It can also be seen that the eastern pacific off the coast of Ecuador has essentially no hurricane activity. This area is our current first choice for an anchor location based on the spatial distribution of lightning and may now solve our wind loading problems as well.

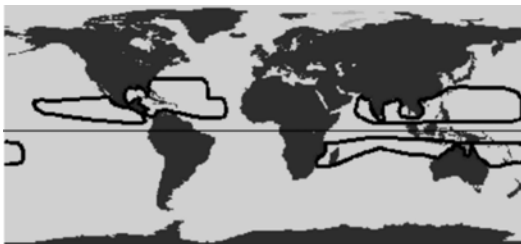


Fig. 10.4.3: The outlined regions indicate the location of hurricane activity.

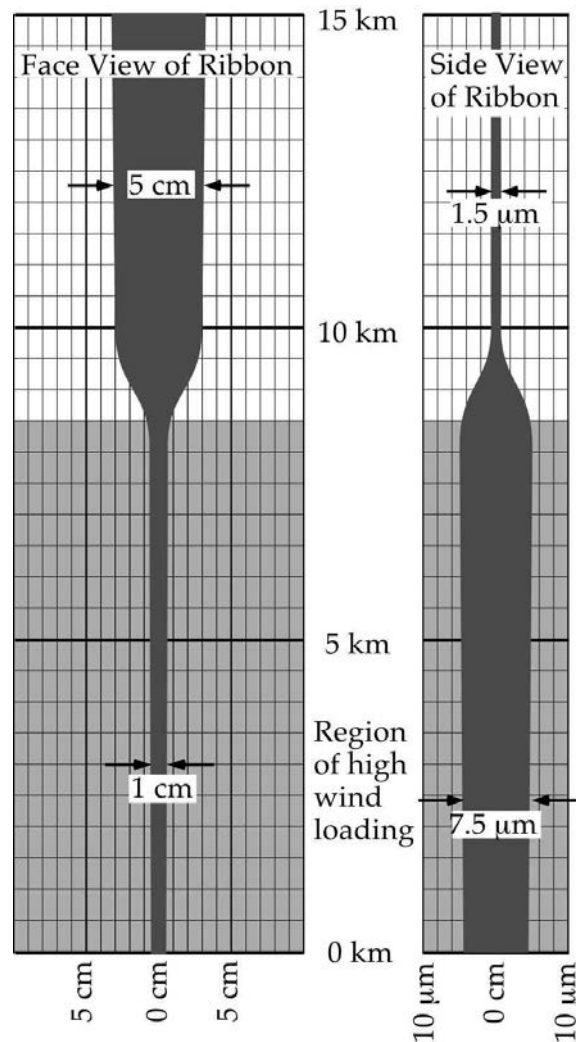


Fig. 10.4.2: Modified cable design to deal with wind loading. Note: In the right hand profile the dimensions are for the average thickness across the ribbon.

Subsection 10.5: Atomic Oxygen

Atomic oxygen exists in the upper atmosphere between about 60 and 800 km with the highest density near 100 km altitude. It is extremely corrosive and will etch the epoxy in our cable and possibly the carbon nanotubes. On NASA's Long Duration Exposure Facility (LDEF) mission atomic oxygen etched carbon fiber/epoxy composites at rates up to $1 \mu\text{m}/\text{month}$ [29], preferentially etching the epoxy in some cases. This high etch rate was only seen on the leading face of the spacecraft where the atomic oxygen is being swept up. On the trailing edge and in the shadowed regions the etching by atomic oxygen was found to be zero in many cases. The reason for this is the thermal velocity of atomic oxygen is about 1 km/s whereas the LDEF satellite velocity was over 7 km/s. For our stationary cable we would expect the etch rate would be down by about two orders of magnitude from what LDEF experienced on its leading edge. On the flip side, LDEF was at about 400 km which places it at an altitude with an atomic oxygen density two times less than the maximum our cable will experience. The bottom line is we should expect to see etching rates of $1 \mu\text{m}/\text{month}$. This etch rate would be sufficient to destroy our cable in a few weeks in the current design (see figure 10.5.1). There are two possible solutions to this particular problem.

The first and probably best solution is to coat the affected segment of cable with a material that is resistant to atomic oxygen as suggested by many of the LDEF experiments. In addition to carbon/epoxy composites, LDEF also had bulk and thin film metal experiments, and metal-coated composites. During the 5.8 year life of the LDEF mission, gold and platinum were unaffected by atomic oxygen, while aluminum and several other metals were found to have minimal degradation. In the metal-coated composite tests it was found that coatings (nickel plus SiO_2) as thin as 0.16 microns could protect the composite from the affects of atomic oxygen. If we coat the affected length of the cable with a metal such as gold or aluminum we will need to make a trade-off between durability of the metal coating under the passage of climbers and minimizing mass so as to not weigh down the cable. Coating thicknesses between 0.02 and 25 microns may be acceptable depending on durability and the density of the coating. What needs to be completed are a set of tests that determine: 1) if the carbon nanotubes as well as the epoxy will be etched, 2) will a metal layer adhere to the epoxy and nanotubes of our cable, and 3) what is the minimum layer of metal that will survive the passage of several hundred climbers.

The second solution is to modify the cable geometry. The baseline, pre-modification cable has an average thickness of 1.5 microns and a width varying from 5 to 11.5 centimeters. This ribbon can be a uniform 1 micron sheet or spaced fibers of 5, 10, 20, 30, up to 400 micron diameter. The larger diameter round fibers would survive much longer in the atomic oxygen environment. As can be seen in figure 10.5.1 unprotected fibers less than about 100 microns

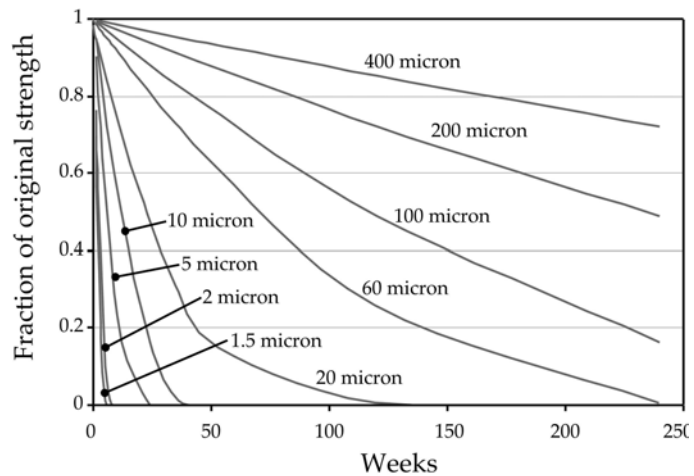


Fig. 10.5.1: Degradation by atomic oxygen of different diameter carbon/epoxy composite fibers as a function

would be insufficient to survive in the atomic oxygen environment long enough for the cable to be strengthened. These large diameter fibers may cause problems for the climbers, be more difficult to add fibers to and have a higher risk of damage by meteors.

Subsection 10.6: Electromagnetic Fields

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 volts/meter, $B(r)$ is the magnetic field, and $v(r)$ is the velocity of the cable relative to the magnetic field. For radii $(r) < 10r_{\text{Earth}}$, $B(r) \sim 0.35 \cdot 10^{-4} r_{\text{Earth}}^3 / r^3$ 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 ($v(r) = 463 r / r_{\text{Earth}}$ m/s) we get potentials from 0.00026 V/m at $10r_{\text{Earth}}$ to 0.016 V/m at Earth's surface. At distances of greater than $10r_{\text{E}}$, the cable is in the interplanetary magnetic field during the day ($B_{\text{ave}} \sim 6$ nT and $B_{\text{max}} \sim 80$ nT) and is in the Earth's magnetosphere at night. 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 μ W at the far end. The cable would quickly radiate this level of heating away into space.

Subsection 10.7 Radiation Damage

The segment of the cable in Earth's radiation belts will experience less than 3 Mrad per year (energetic electrons and protons) [Daly, 1996]. Studies of epoxy/carbon fiber composites (epoxy/nanotube composites would be expected to be comparable or better) have found them to be radiation hard to greater than 10^4 Mrad [Egusa, 1990; Bouquet, 1979]. This would allow them to survive more than 1000 years in the expected environment.

The other radiation damage that must be considered is that of solar UV. Often specific materials can be corroded by ultraviolet radiation and this must be considered when selecting an epoxy for the cable construction.

Subsection 10.8: Induced Oscillations

Initial work by Pearson, 1975, on oscillations induced by the moon, sun and motion of climbers found the problems avoidable. However, since we have a fairly different system scenario the calculations need to be repeated. In Pearson's work, he had a cable of 144,000 km long with no counterweight on the end and examined only taper ratios above three. Our shorter cable will increase our characteristic frequency, the counterweight will essentially fix the upper end of the cable (doubling our frequency from the case Pearson calculated) and our smaller taper ratio will decrease the frequency.

If we examine the standard oscillation of a string under tension [Nagle, 1996] with the ends fixed, we find our system is very close to the ideal case. The initial-boundary value problem for the standard problem is:

$$\frac{\partial^2 u}{\partial t^2} = \frac{\partial^2 u}{\partial x^2}, \quad 0 < x < L, \quad t > 0, \quad (1)$$

(essentially $F=ma$ for each segment of the string)

$$u(0,t) = u(L,t) = 0, \quad t \geq 0, \quad (2)$$

(boundary values for the string having fixed ends)

$$u(x,0) = f(x), \quad 0 < x < L, \quad (3)$$

(defining the initial position of each segment of the string)

$$\frac{\partial u}{\partial t}(x,0) = g(x), \quad 0 < x < L. \quad (4)$$

(defining the initial velocity of each segment of the string)

where u is our equation of motion, L is the length of the string, $f(x)$ is the initial location of the string, $g(x)$ is the initial velocity of the string and $\frac{\partial^2 u}{\partial x^2}$ is equal to the ratio of the tension to the linear density of the string. This assumes: no gravity, the string is perfectly flexible, the string is a constant linear density, the tension is constant and no other forces are acting on the string. This doesn't sound like our situation at all. Well, let's look at it a little closer. We have gravity, but that is what is giving us the tension and it is along the cable in our case. For any individual segment of the cable, the force applied by gravity is small compared to the tension. Our cable is pretty much perfectly flexible, the width is much less than the length. Our cable does not have a constant linear density or constant tension. But let's look at where these two come into our calculations. Equation (1) is equivalent to $F=ma$ for each segment of the cable. The only place where the design of the cable comes in is in $\frac{\partial^2 u}{\partial x^2}$. And $\frac{\partial^2 u}{\partial x^2}$ is also where the restriction on constant tension and linear density comes into play. The one unique thing about our cable design is it is designed specifically such that the tension for any segment is exactly proportional to its cross-sectional area (or linear density). To be precise, to correct these equations we would need to put in a function of x in equation (1). However, because of our specific relation between tension and linear density this function is defined as 1 at all locations and has no affect on our problem. The initial boundary value problem we have stated above is a very close match to our situation. The last constraint was that there were no other forces acting on the string. To a large extent this is true, only the moon, sun and climbers will act on our cable. These are small forces that can pump oscillations but not dramatically change the characteristic frequency of the cable.

The solution to this problem is given in many differential equations textbooks and gives a characteristic frequency for our cable of

$$= \frac{2 L}{n \sqrt{\quad}}$$

where L is 9.1×10^7 m, $\sqrt{\quad}$ is 7.1×10^3 m/s and n is 1, 2, 3, 4, The first mode has a period of 7.1 hours. This period is sufficiently far from 12 hours (the sun), 12.5 (the moon) or integral fractions of these so our cable should not be pumped by either the sun or moon. A cable 15% shorter than the one we propose (76,000 km) could have serious problems. Small oscillations or traveling waves that may be induced by wind or meteors can also be actively damped out at the base of the cable if a cable displacement monitoring system is implemented to detect any movements in the cable.

One oscillation that Pearson investigated was that of transverse waves induced by climbers. The bottom line on this oscillation is that large oscillations can be induced when the climber transverses the length of the cable in one period of the cable's characteristic frequency. (Pearson assumed no counterweight so had the climber traveling twice the length of the cable during one period.) Since we just calculated our cable's characteristic period to be 7.1 hours we will only need to worry about this particular affect when we plan to have climbers traveling at close to 10,000 km/hr.

Subsection 10.9: Environmental Impact

When considering the construction of a space elevator the possible environmental impacts must be examined. Two of those environmental impacts will be considered here. The first is the possibility of discharging the ionosphere and the second is the impact if a space elevator were to be severed and fell back to Earth.

Discharging the Ionosphere

The charge production rate in the ionosphere ranges between 2000 and 6000 $\text{q/cm}^3/\text{s}$. For an area around the cable of $1\text{km} \times 1\text{km}$ and 500km in vertical extent this relates to 1×10^{25} q/s or 625,000 C/s. With a resistivity 10^{-4} m for carbon nanotubes, a 20-ton capacity cable (2 mm^2 cross section) would have a minimum resistance of roughly 5M . For the cable to discharge the ionosphere at the same rate as charge is being produced would require a current of 625,000 Amps to flow through the cable. To produce this current a voltage difference of $\sim 3 \times 10^{11}$ Volts would be required between Earth and the ionosphere. The measured electric field under thunderclouds just before a lightning strike is 10 – 20 kV/m. If we extend this electric field up to the ionosphere (which does not occur but should be a worst case) we find the static voltage potential would be less than 2×10^9 Volts. At this voltage difference with no redistribution of charge in the ionosphere we could discharge an area 100m around the cable. Since we have assumed the most conducting cable possible (in reality it would probably be down by orders of magnitude due the epoxy sections) and the highest potential difference conceivable it is more likely that only a small volume of centimeters radius would show any affect from the cable's presence.

Severed Cables

If a cable is severed the lower segment will fall back to Earth while the upper portion floats outward. The worst case would be if the counter mass breaks off the far end of the cable and the entire 91,000 km of cable falls back to Earth.

Depending on the location of the break, the epoxy used, the dynamics of the fall, etc. the cable will re-enter the Earth's atmosphere at a velocity sufficient to heat the cable above several hundred degrees Celsius (figure 10.9.1). If the cable is designed properly, the epoxy in the cable composite will disintegrate at this temperature. This means the cable above a certain point will re-enter Earth's atmosphere in small segments or carbon nanotube / epoxy dust. About 3000 kg of 2 square millimeter cross-section cable (20 ton capacity) may fall to Earth intact and east of the anchor. Detailed simulations will be required to determine the possible sizes of segments that will survive and the health risks associated with carbon nanotube

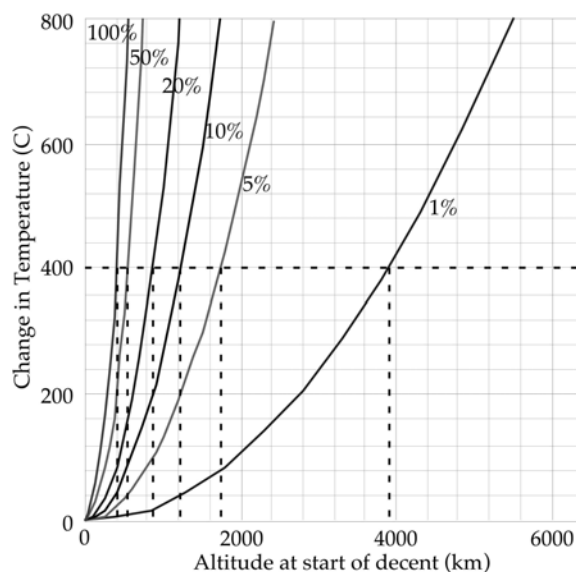


Fig. 10.9.1: Re-entry temperature of the cable as a function of starting altitude and fraction of energy deposited in the cable. Depending on the fraction of energy that goes into the cable (1% - 100% shown in the plot) as opposed to going into the air, cable lengths of 400 to 4000 kilometers could re-enter without disintegrating.

and epoxy dust. In terms of the mass of dust and debris that will be deposited, we can compare what will happen to what naturally happens now. Each year 10,000 tons of dust accrete onto Earth from space, the additional 750 tons of the first cable will increase that year's infall by 7.5%. A larger 1000-ton capacity cable would have a mass of 30,000 tons or roughly equivalent to 3 years of normal global dust accretion. Further investigations are required to determine the environmental impact of depositing this much dust along the Earth's equator.

In the opposite case where the break is at the bottom of the cable, the entire structure would float up away from Earth. The cable would remain in orbit with the lower end hovering above the Earth at some low altitude. Re-connecting the lower end may be a possibility, but we will not speculate on that here.

In all cases, there will be some amount of time (hours to days) between the initial break and any substantial change in the configuration of the cable. Various scenarios can be derived for saving the cable or stopping it from re-entering during this delay but these will all greatly depend on many aspects of the design and current state of the cable at the time of the break.

In any analysis of the environmental impact the possibility of a falling cable and the damage it will cause must be compared to the alternative which is continued use of rockets. During rocket use both pollutants from the burning fuel and from the re-entry of the spent rockets must be considered. For example, each Titan IVB has a dry mass of 65,000 kg, much of which ends up re-entering and burning up in Earth's atmosphere. The Titan IVB also burns roughly 500,000 kg of propellant. Our proposed 20 ton capacity cable has a mass of 750,000 kg. A strictly mass comparison is far from the proper comparison to make but it gives a rough idea of scales of the environmental impacts we need to compare.

Chapter 11: Budget Estimates

Estimating the cost of building and operating a space elevator at this stage of development is challenging, but we feel for at least large segments of the program we can get cost estimates that can guide future decisions. We feel we have good cost estimates for much of the program with the cable production being the largest uncertainty. We have also tried to make conservative cost estimates. The bottom line is that the space elevator could be built at a cost comparable to many U.S. endeavors.

Launch for Initial Spacecraft

As we have progressed through this study several aspects of our program have changed. The launch vehicle is one of them. Due to results of further investigations into the deployment of a cable from orbit and to eliminate on-orbit splicing of the initial cable we have modified our deployment scenario. In our current plan we will send the entire system to low-Earth-orbit on shuttles, assemble the pieces and then send the large assembled spacecraft to geosynchronous orbit (see Chapter 5: Deployment). The vehicle to reach LEO can be either a standard shuttle (7 launches) or the yet-to-be-constructed shuttle-C (3 launches). To go from LEO to GEO we propose to use a system based on the Centaur for our calculations. The standard shuttle option will cost approximately \$500M in current dollars per launch (based on \$245M in 1988 dollars) and the Centaurs are roughly \$30M each. This gives us a total transportation cost to GEO of \$3.7B. If we go with the shuttle-C launch option we will have an additional \$3B - \$7B for development and \$2B less for the four fewer launches. We will get a larger first cable and avoid some of the constraints on launching propulsion systems with the shuttle-C option so it should be considered. The launch costs on the shuttle-C option will be \$4.7B - \$8.7B. To reduce costs it is also possible to launch some segments on other commercial vehicles. This could save up to \$500M in launch costs (an Atlas V/Centaur with 20,000 kg to LEO capacity is \$90M) and possibly months on the deployment schedule since the commercial vehicles would use different launch facilities from the shuttle.

Initial Spacecraft

The initial spacecraft will be relatively simple in design but one of the larger systems ever launched. The main purpose of the spacecraft is to take its cargo (the cable) to orbit and deploy it. There are no complex optics or electronics, but there are mechanical systems. We believe this spacecraft could be built for approximately \$1B.

Cable Production

This is the most difficult component of the program to get an accurate cost estimate for. The cables (208) such as we are discussing have never been produced before. It must be a completely automated process from feeding in the raw materials to final testing. Besides the complexities and quality requirements of the cable itself, large-scale production as we are discussing is nothing new to many industries (textile, automotive, fiber optic, electronic, etc.).

Climbers

The 207 climbers we intend to send up the cable will all be the same basic design but need to deal with the ever increasing cable sizes. Hopefully the climbers can be designed in a modular form so that for some large number of climbers the same components can be used just

in larger quantity. For example, the first 10 climbers may have five motors to pull them up the cable. The next 10 may have several structural components and one additional motor added without substantial modification to the rest of the climber. If designed properly each of the 207 climbers will not be a custom production. Based on small spacecraft work we believe that \$20M per climber (excluding the cable cost) is a reasonable estimate with the first climber being more expensive and the later ones being less expensive.

New Tracking Facility

Radar systems such as the Haystack Observatory have begun tracking objects down to 1 cm in size. Optical systems, which have some advantages, (and disadvantages) are also coming on line. NASA has already requested that the current space surveillance network be upgraded to track debris down to 1 cm with improved accuracy. It has also been suggested the upgrade include moving the facilities to the equator. More details are required, but if the upgrade were to occur, it may satisfy all of the foreseeable tracking needs of the space elevator. If the upgraded space surveillance system does not come online before a space elevator is undertaken then a set of tracking facilities (radar similar to Haystack or a phased array or optical as suggested by Ho³⁹) would be required to be built. A reasonable estimate is that five new facilities would be required along the equator. Five facilities would allow good tracking and not place the elevator in jeopardy if one or two tracking facilities are down. Based on estimates for a new radar observatory each facility could cost less than \$100M (Berkeley's One Hectare Telescope for example is \$25M) including high-speed computing facilities.

Johnson Space Center has also conducted a study on constructing a new set of tracking facilities⁴⁰. The system that was proposed used current technology (X-band phased arrays and dishes) and U.S. locations. The total estimated cost of one billion dollars to build and 100 million dollars per year to operate were given without any breakdown but are roughly close to our estimate above.

We will use what we feel is a conservative cost estimate of \$1B for construction. Operations will be broken out with the rest of the program belows.

Anchor Platform

If a platform modeled after the Sea Launch facilities is selected, the total cost of this system would be less than \$300M. This does not include a power beaming station (see below) or unique new facilities that may be desired such as a nearby, floating airstrip.

Power Generation Station

The current engines on-board the Sea Launch platform generate 20 MW of mechanical power. A similar system could be used to generate the electrical power needed by the laser beaming system. If the total efficiency of the beaming system is greater than 5% (see power beaming section) then this system could supply 50% of the power required for operating a 20 ton capacity elevator. Either a larger power generation system or two will be required for our purpose but for now we will use this system for our baseline. We will need a separate beaming facility in addition to the one at the anchor and will probably want a backup system at each facility. For a budget estimate we will use \$100M (a very conservative estimate based on the *Sealaunch* program) for each of the four power generation systems. The total power generation budget estimate is \$400M.

Power Beaming Facility

For our cost estimates we will use a laser beaming system. The beaming system will consist of the facility infrastructure, high-power lasers and a large deformable mirror. We will want both the power beaming facility located at the anchor and a separate beaming facility on a second platform on land to improve the transmission duty cycle. The facility costs for the separate beaming station will be the cost of the platform (\$300M) if an ocean station is selected and possibly \$10M per land site. The facility costs at the anchor platform could be an additional \$100M for modifications. The Compower power beaming system is well along in its development and has accurate cost estimates for that system²⁰. The lasers are \$100M each (fixed price from Berkeley for a 1 MW system) and the deformable mirrors are \$125M each including infrastructure. We will need 4 MW of output laser power for the initial cable so each beaming station can be assumed to have 4 laser systems and between one and four mirrors depending on how well the beam paths can be combined. If we assume the beam paths can not be combined we will need four completely independent systems. Each laser beaming station will then be \$900M (\$525M for single mirror system) if no savings are assumed because all the systems are identical. This would mean we should conservatively budget \$2.2B (\$1.45B for single mirror systems) for the two beaming stations with each on an ocean platform.

Operations

At this point, we will include operations for the first ten years of the space elevator. It is obvious the cable operations will go well beyond this but this will cover everything we have discussed for the initial cable. JSC's estimate for operating the tracking facility is \$100M per year³¹. There was no breakdown on this cost, so we will take it at face value. For operating the space elevator we will assume two platform facilities with crews (20 per facility), technical staff (30 per facility), support personal (30 per facility), and administration (10 per facility). This is a total of 140 people (this is roughly equivalent to the *Sealaunch* program). If we take an average salary of \$100k and 100% overhead we have a total yearly operations budget of \$28M. We will also assume there will be personal located back in the states of equal numbers. This gives us a yearly personnel budget of \$56M plus the \$100M slated by JSC for the tracking facilities.

Miscellaneous and Contingency

At this stage of a program accurate cost estimates are difficult especially for something as unique as the space elevator which really has no prior completed project for comparison. We have implemented a 100% cost contingency to cover items that have been overlooked or may show-up later in the program and to cover growth in costs.

Summary

The summary of our budget estimate is in table 11. 1. This study has clarified the cost of many of the space elevator subsystems (relative to the original estimates in our proposal). There is still uncertainty in the cost of the cable production, on-orbit operations, and some in the initial spacecraft and climbers. Due to the uncertainties in these areas we have increased our contingency. These estimates are based on technical requirements, political costs are not included.

Table 11.1: Budget Summary

Original Component	Original Cost Estimate	Revised Cost Estimate	Comment
Launch costs to GEO	\$1.4B	\$3.7B	Changed to 7 shuttles with Centaurs
Cable production	\$5B	\$5B	Still difficult to estimate
Spacecraft	\$1.2B	\$1B	One large SC instead of 4 small ones
Climbers	\$1.25B	\$4.2B	\$20M instead of \$5M each, 207 instead of 250
Power beaming station	\$10B	\$2.2B	Based on Compower system, two systems on ocean going platforms
Power gen. station	\$4B	\$400M	Based on <i>Sea Launch</i> program's power generation system
Anchor station	\$5B	\$300M	Based on <i>Sea Launch</i> program's ocean-going platform
Tracking facility	\$1B	\$1B	New facilities based on several existing programs and a NASA study
10-year operation		\$1.56B	Now broken out separately
Misc. and cont.	\$10B	\$20B	100% contingency
TOTAL	~\$40B	~\$40B	Coincidence

Optional Additions

Several additions can be made to the overall space elevator program that would be of considerable benefit which include:

1. A nearby or attached floating airport based on the Japanese MegaFloat system. Japan has been working on a floating platform with kilometer dimensions for use as an airport. A floating airport in close proximity to the anchor platform would allow for emergency delivery of components or personnel.
2. A dedicated ship for transporting personnel, supplies, equipment, climbers, etc. to and from the mainland (figure 11.1). This may be viewed as more of a necessity but in reality commercial shippers and transport vessels can be used.
3. High-tech development, design, construction and repair facilities located on-board the anchor or nearby platform. A facility such as this may be useful in unpredicted or unusual circumstances such as a climber that has been damaged in delivery, dealing with a seized climber, understanding cable or climber problems that arise, etc.

4. Future large-scale facilities. As the cable grows to transport 10^6 kg payloads and people, much larger facilities will be required. What has been discussed here are only facilities for the first cable. Facilities that should be considered in the future include a megafloat-type platform for personnel in-transit, large staging facilities and facilities for supporting a long-term population.



Fig. 11.1: Picture of the Sea Launch dedicated ship Sea Launch Commander used for transport of personnel, launcher, and supplies and for controlling the launch operations. A similar vessel would be valuable in the space elevator program for delivery of personnel, equipment and supplies.

Beyond the first cable

After the first cable is complete, the second and following cables will be considerably easier, faster and cheaper to build per kilogram of capacity. Climbers can be sent up the first cable deploying and building the second cable as they climb. In this case a cable of comparable size to the original can be made in 7 months instead of the 26 months of the first. If we assume we work out some of the designs and difficulties in building the first cable and eliminate the non-recurring costs we find the second cable can be built for under \$15B (table 11.2). The third and subsequent cables will cost less than the second. The value of these cables are no less however and, if it were so decided, some of these subsequent cables could be sold as completed units to private industry or other entities to recoup the cost of the entire space elevator program. When considering larger cables the scaling of the climbers and power beaming systems must be taken into account.

Table 11.2: Cost of Producing the Second Cable

Component	First Cable	Second Cable
Launch cost to GEO	\$3.7B	0
Cable production	\$5B	\$3B
Spacecraft	\$1B	0
Climber	\$4.2B	\$3B
Power beaming station	\$2.2B	\$1.6B
Power gen. station	\$400M	\$400M
Anchor station	\$300M	\$300M
Tracking facility	\$1B	0
10-year operation	\$1.56B	\$1B
Misc. and contingency	\$20B	\$5B
TOTAL	~\$40B	~\$14.3B

Chapter 12: Schedule

Based on our proposed design we have estimated a realistic schedule for deployment of a space elevator once the critical technology development efforts are complete. This schedule is based on the technical aspects of the program only. Some of the baseline time constants used to produce this schedule include:

1. Time to double the size of the cable:170 days
2. Time to produce the first 20,000 kg capacity cable: 28 months
3. Time to upgrade a 20,000 kg cap. cable to a 10⁶ kg cap. cable:36 months
4. Time between climbers:4 days

In addition, we have laid out one possible scenario for future utilization of the space elevator. We have assumed that after deployment of the first several space elevators the system designs, materials, construction techniques, and deployment techniques will improve reducing the time and cost of future elevators.

Allow me to expand on each of the items in the schedule briefly.

1. Spacecraft and Climber Design: The design is always the most critical stage of any space program. The three years that we are allowing here should actually be the final design stage. Again, this is starting after all the technologies have been worked out and we are assuming here that people will do lots of thinking about all aspects of the space elevator before the program begins.

2. Initial Spacecraft Construction: After a detailed design process building the initial spacecraft should be feasible within a 3.5 year time period.

3. Initial Spacecraft Launch: This includes launching the various spacecraft components and the quick on-orbit assembly. This whole process should be designed to take no more than a few months. This will require streamlining the shuttle launches and utilizing more than one type of launch vehicle.

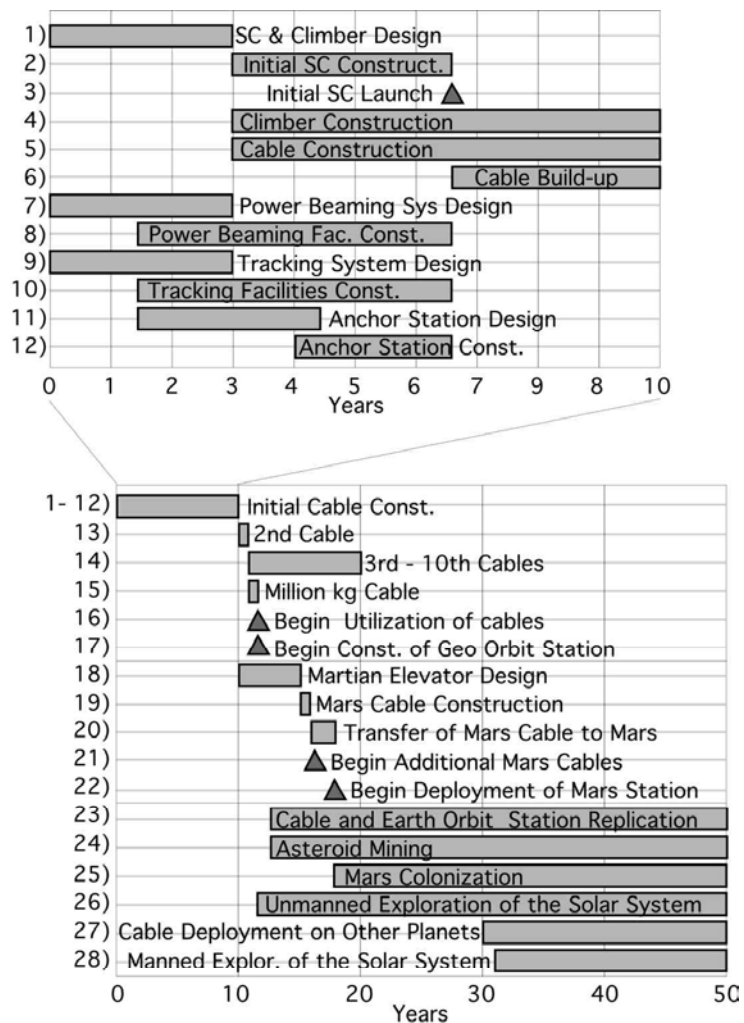


Fig. 12.1: Deployment schedule for a space elevator and possible long-term utilization scenario.

4. Climber Construction: This schedule item includes the all of the climbers. The climber design and facilities to produce them must be such that the entire 207 climbers can be delivered during this seven year period with extremely few malfunctioning units. If the climbers can not be produced during this period, there is a substantial risk of program failure (the cable coming down). This point emphasizes the need for a streamlined program and designs that are expandable yet simple.
5. Cable Construction: This schedule item includes construction of the initial cable and all subsequent cables to be taken up the elevator. This item has the same cautionary note as the climber construction above. Each of the 208 cables must be produced with almost perfect quality and on schedule.
6. Cable Build-Up: The first year of this is the most critical. After the first year, the cable is more stable and less vulnerable to damage by meteors.
7. Power Beaming System Design: This again should be a final design stage based on the current systems. All technology development needs to be completed prior to this stage.
8. Power Beaming Facility Construction: Based on the commercial Compower system, this should be very reasonable schedule to build and test the power beaming system. Once again, this is a critical system that will have backups because a power beaming system must operate continuously for the entire time during the climbing stage.
9. Tracking System Design: Since the proposed system is based on current systems this should be a simple schedule target.
10. Tracking Facilities Construction: Based on current technology and systems five years for construction should be feasible. The tracking system must be up and have a complete database of objects prior to launch. This again is a critical system that must be operational during the entire life of the cable.
11. Anchor Station Design: Based on the *SeaLaunch* program, this schedule should provide plenty of time for a proper design to be completed.
12. Anchor Station Construction: The *SeaLaunch* platform was constructed in 18 months. Combined with the design stage the time we have allotted will be sufficient to build and test the anchor platform.
13. Second Cable: Once the first cable is in place, building additional cables becomes much simpler, less risky and less expensive (see budget section). It would take roughly 200 days to put the second cable in place based on our analysis. A second cable would need its own anchor station and power beaming facilities that could be constructed during the first climbing stage (#6). The importance of building a second cable immediately is severalfold. First it gives a redundant system in case a problem occurs with the original cable. Second, the two cables are completely independent and can address different program directions. One cable can be producing additional cables while the other is launching commercial satellites or building up to a much larger size to address manned occupation of space.
14. Third through Tenth Cables: A good strategy would be to use one of the first two cables to start producing additional cables. In 200 days one of the two original cables could produce a second identical cable. The process can be repeated with both cables as often as is needed. For example, utilizing one of the initial two cables to produce additional cables we could have a total of eight cables in 600 days (much less than the nine years we have allotted in the schedule). A point to remember is each of these would require their own anchor and power beaming systems. The advantage of producing multiple cables is they can be dedicated or

- sold to specific users (military, commercial, foreign, and private) to bring in revenue and cover the initial development costs or utilized for different specific tasks.
15. Million Kilogram Cable: The larger cables will be essential to any manned activities. The larger cables will also further reduce the difficulty in producing additional cables (a 20,000 kg capacity cable could be produced with two climbers on the larger cable). This schedule estimate of 36 months is based on continuously running climbers up the initial cable.
 16. Begin Commercial and Scientific Utilization of Cables: At this point, the cables are stable and redundant cables are in place. What this means is that the cables will remain in orbit for many decades with minimal maintenance (anchor maneuvers). This is the beginning of the real use of the space elevator. Commercial satellites can be taken to orbit every few days and much larger unmanned scientific missions can be deployed in Earth orbit and to the other planets.
 17. Begin Construction of Geosynchronous Orbit Station: With a large cable in place (two is preferable) construction of a human station at geosynchronous orbit can begin. Each climber will be roughly the size of the shuttle orbiter so a station can be built quickly and easily. Depending on the size, complexity and preplanning for the station, the time to habitability could be as little as a month. After construction on Earth a large station (70 times the mass of the shuttle orbiter with 20 million kgs of consumables) with hundreds of permanent occupants could be placed in orbit in a year (90 climbers). A second large cable is preferred for downward transport.
 18. Martian Elevator Design: A prime example of the utility of the elevator is in manned exploration and colonization of Mars. The design of the Martian elevator is very similar to an Earth one and should be straight forward at this point in the program. The schedule time we have allotted should be more than sufficient. We should also point out here we have left a quiet period of several years during which the Earth cable will be utilized for construction of stations, launching satellites and basically getting accustomed to using the elevator.
 19. Mars Elevator Construction: Almost all of the construction time is on the ground with construction of the cable, spacecraft and ground module. Assembling the Martian elevator utilizing the Earth elevator and launching it to Mars will be fairly quick.
 20. Transfer of Mars Cable to Mars: Travel, orbit insertion and deployment time.
 21. Begin Construction and Deployment of Additional Mars Cables: By the same arguments as above it is best to have redundant cables. Each of these will be exactly identical to the first.
 22. Begin Deployment of Mars Station: After the initial or first two cables have successfully deployed on Mars a manned module can be sent to Mars. Part of the module will remain in Mars synchronous orbit attached to the cable and part will drop down the cable to the Martian surface. A return module will be used to complete the journey.
 23. Cable and Earth Orbit Station Replication: Once the space elevator system is established many cables and geosynchronous stations will be constructed. This will be a permanent activity.
 24. Asteroid Mining: Resource utilization including mining asteroids, tapping power in space and sending it down to Earth, microgravity industries, etc. will become permanent activities.
 25. Mars Colonization: We have this beginning with the first Mars station deployment but in reality it is easily seen how the system we have described can be replicated many times to basically allow for large scale colonization of Mars.
 26. Unmanned Exploration of the Solar System with Large Spacecraft: In the current situation, all planetary missions are mass constrained. The space elevator would allow for very large

(million kilogram) probes to be sent to all parts of the solar system for detailed and long-term studies.

27. Cable Deployment on Other Planets: Earth and Mars are the most ideal planets for establishing cables from our perspective. Once the technology is established, our moon, Callisto and Ganymede are the next most likely candidates as well as a free spinning colony.
28. Manned Exploration of the Solar System: Once a cable is established at a location such as Ganymede, it is a matter of determination to establish a human presence. My timeline on this is obviously a very rough guess but depending on the human determination, it could happen on the timescale we present here.

Looking at this schedule there is an important fact to realize. The slow part of the schedule is at the beginning if we assume adequate funding is available. Let's consider two roughly equal entities (governments, private enterprise etc.). At year zero, entity one begins building a space elevator behind closed doors. The second is looking at building a space elevator and thinks it is important but has not begun building it yet. At year five the news gets out that the first entity is building the space elevator. The second now jumps into its program and starts building. At year ten the first entity has its first elevator operating and the second entity is 18 months from launch of its initial spacecraft. At year fifteen the first entity has six cables up including two 10^6 kg cables, has a manned station at geosynchronous, has recouped much of the construction cost through selling two cables and through hundreds of launches on its eight cables, and is beginning construction of a Mars cable. The second entity has up its first cable. Note that two additional entities also have cables now because of entity one's sales. At year twenty, entity one is making billions from the tens of cables it has produced, has a manned station on Mars, has a hotel at Geo station which now has a permanent population of over one hundred. Entities two, three, four, five, ... each own a handful of cables and are trying to compete with entity one. This may sound a bit fanciful but if my estimate of a possible schedule (figure 12.1) is correct then this particular scenario could occur. My scenario events come directly from figure 12.1. The point of this discussion is to illustrate the unique advantage of even a single cable. With the capabilities of the space elevator development of space could occur surprisingly quick with the lead being held by the entity that puts up the first cable, all else being roughly equal.

Chapter 13: Future Work

With the completion of this initial study we find no reasons a space elevator can not be built and find many reasons to build it. We have examined all aspects of the space elevator but there is obviously plenty of work yet to be done before a complete functioning space elevator can be built. Everything from spacecraft structures and motors to the weather need to be examined further. Of these follow-up studies the most critical ones are:

1. Nanotube production: Can nanotubes be produced with the required properties? How easily can nanotube production be scaled up?
2. Small-scale cable design: What is the best design for the cable on small scales (microns to meters)?
3. Cable production: What are the difficulties in producing the cable and at the rates required?
4. Full-up power beaming test: How well does the complete system work at the required power levels?
5. Cable splicing on-orbit: What is the best method to attach additional small fibers to the edge of the initial cable?
6. Damage by small, grazing-incidence meteors: High-velocity impacts tests are required to determine the seriousness of grazing incident meteors. All meteor sizes from 10 microns to 5 millimeters and all impact angles should be tested on different cable designs.
7. Protection from Atomic Oxygen: Are carbon nanotubes susceptible to atomic oxygen erosion? What are the optimal coatings for protection against atomic oxygen and can they be coated onto carbon nanotubes and epoxy? What is the wear rate of this coating under high-speed climber traffic?

Chapter 14: Summary

Since its conception in 1960, the space elevator has appeared primarily in science fiction and concept overviews. With this manuscript we have attempted to present a complete quantitative analysis of the problems that will be encountered designing, constructing, deploying and utilizing a space elevator. We have started with the basic concept and existing technologies and put forth a system design and deployment scenario. We have addressed the environmental problems this system must survive and what will happen if it does come down. We have presented one possible deployment schedule and a cost breakdown based primarily on existing systems. We have presented the design trade-offs and how the space elevator could be utilized. What we have found is that an extremely valuable space elevator can be built in the near future with acceptable risk and less funding than some current space programs.

This manuscript is not intended to be the final word on any aspect of the space elevator. It is intended to be a starting point. The next stage is not to form large design committees but to get armies of graduate students and researchers examining each individual aspect of the scenario we have presented. Carbon nanotube composites, meteor impacts, weather, orbital mechanics of the deployment, induced oscillations from every source, power beaming, on-orbit operations, electric propulsion, atomic oxygen, nanotube and epoxy coating, climber design, cable spooling and cable design all need to be studied and can be done by many small programs. Once the individual efforts have produced the needed information, a technically-driven, fiscally-responsible team of committed individuals can be formed to build the space elevator. With a concerted and objective effort we could begin construction of the space elevator in the coming decade.

With the construction of multiple space elevators we would see the beginning of new commercial markets, new resources and possibly a true space-fairing society. Just as the transistor was the first small step in the current computer age, the space elevator may be the step that takes our children to the stars.

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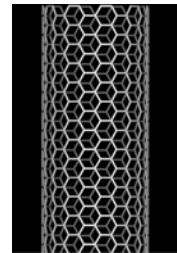
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Definitions and Basics

Adaptive Optics: A technique for reducing the blurring effects of light travelling through the atmosphere. The problem is that when you want to use a large mirror for astronomy or, in our case, to beam power to space the light in different parts of the large beam are distorted differently by the atmosphere. To eliminate this problem adaptive optics has been developed. Adaptive optics is a technique to rapidly distort the mirror to correct for these atmospheric distortion and reconstruct the blurred beam.

Atomic oxygen: Single oxygen atoms as compared to oxygen molecules (two oxygen atoms) found in air. Atomic oxygen is found in the upper atmosphere where it has been created by solar radiation. It is extremely reactive and corrodes most materials readily.

Carbon nanotube: A carbon nanotube is an ordered molecule of pure carbon as illustrated at right. The diameter of a carbon nanotube is on the order of 10 nanometers (1×10^{-8} meters, 4×10^{-7} inches). Per kilogram of mass, a carbon nanotube theoretically will be over 30 times as strong as Kevlar and 250 times as strong as steel.



Structure of a carbon nanotube



Centrifugal acceleration is the outward acceleration experienced by an object travelling in a circle. For example, on a rapidly spinning merry-go-round you will have to hold on to keep from getting thrown off. The outward 'force' you experience in this case is due to centrifugal acceleration. In our case the cable experiences an acceleration away from the Earth because of its orbital velocity. This translates into an upward force on the cable from the perspective of someone standing on Earth.

EMF or Electromagnetic Fields: When there is a electrical potential difference between two points or a magnetic field then in general it can be referred to as an electromagnetic field. In our discussions here we use electromagnetic fields to refer to the magnetic fields near Earth which the space elevator can pass through and the electrical potential fields that can build up in a storm and produce lightning.

Geosynchronous orbit is where the downward gravitational acceleration and the upward centrifugal acceleration are equal for an object stationary above a point on Earth. Geosynchronous orbit is at an altitude of 35,800 km.

GPa: Gigapascals is a unit of pressure which can be used to express the strength of a material. It is 10^9N/m^2 or $1.5 \times 10^5 \text{psi}$. This means that a 1 inch square cable of a material with a tensile strength of 1 GPa could lift a 150,000 pound load.

Gravity Gradient: In the context of our discussions, gravity gradient is used in reference to the orientation of our cable. For a structure as large as our space elevator different parts of it will feel different amounts of gravity. The end nearest the Earth will feel considerably more pull from Earth than the furthest end. What this tends to do is to orient objects in orbit such that their longest dimension points toward the center of the Earth.

Kilogram (kg): A kilogram is a metric unit of mass equivalent to 2.2 pounds (in a standard Earth gravity environment).

Kilometer (km) is a standard metric unit of length equivalent to 0.62 miles.

Low-Earth Orbit: These are generally circular orbits with several hundred kilometer altitudes as compared to geosynchronous orbit for example which has an altitude of 35,000 km. The shuttle and most other satellites operate in low-Earth orbit.

Power beaming: The act of sending power over large distances using energy beams (lasers, microwaves, etc.) as compared to more conventional methods that use wires and electricity.

Shuttle-C: The shuttle-C is an unmanned version of the standard U.S. Space Shuttle. The “C” in this case refers to “Cargo”. This is an option that has been discussed and studied but not implemented. The payload of the Shuttle-C would be roughly three times that of the standard Space Shuttle.

Space Debris: Space debris refers to the remnants of rockets, satellites and other objects left in space by man’s activities. Most of this debris is located in orbits with altitudes between 500 and 1700 km.

Taper ratio: The taper ratio as we use it in this manuscript refers to the ratio of the cross-sectional area of the space elevator cable at geosynchronous to the cross-sectional area of the cable at the Earth end.