The space elevator: an ideal application for the free electron laser

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ABSTRACT

All space activities rely completely on rockets to get into space. Advanced propulsion systems are being examined by NASA and others but few if any of these technologies, even if perfected, can provide the high-volume, low-cost transportation system required for future space activities mankind hopes for. A system with the required traits is the space elevator. The space elevator, a cable that can be ascended by mechanical means from Earth to space, would reduce the cost of getting into space by a factor 100 or more while increasing launch capabilities dramatically. Under a NIAC grant we have laid the technical groundwork by examining all aspects of a first elevator. For a cost of $40B the first space elevator could provide low-risk, inexpensive access to space within the next 15 years. A free-electron laser power beaming system is critical to the success of the space elevator, no other system has the performance required to provide power to the climbers. Using the free-electron laser power beaming system the space elevator could efficiently provide inexpensive access to space for placing satellites, human colonization and placement of space-based solar power satellites that could provide large quantities of renewable clean power.

1. INTRODUCTION

The modern version of the space elevator concept was first proposed by Artsutanov[1]. In the following years the concept appeared several times in technical journals[2,3,4] (Isaacs, 1966; Pearson, 1975; Clarke, 1979) and in science fiction[5,6] (Clarke, 1978; Stanley Robinson, 1993). The modern space elevator grew out of elongating a geosynchronous satellite until it eventually touched Earth. The space elevator is essentially a cable with one end attached to Earth and the other end above geosynchronous altitude. Once in place the cable can be ascended with mechanical climbers.

A quantitative and comprehensive analysis of the space elevator concept[7] (Edwards 2000, see figure 1) was funded by NASA's Institute for Advanced Concepts (NIAC). This report examined all aspects of the concept and proposed a complete design for the design, deployment and operation of the first space elevator. A small, carbon nanotube composite cable capable of supporting 495 kg payloads would be deployed from geosynchronous orbit using eight shuttles and liquid or solid fuel-based upper stages. Climbers (288) are sent up the initial cable (one every 71 to 119 hours) adding cables to the first to increase its strength. After 2.5 years a cable capable of supporting 20,000 kg climbers (13,000 kg payloads) would be complete. The power for the climbers is

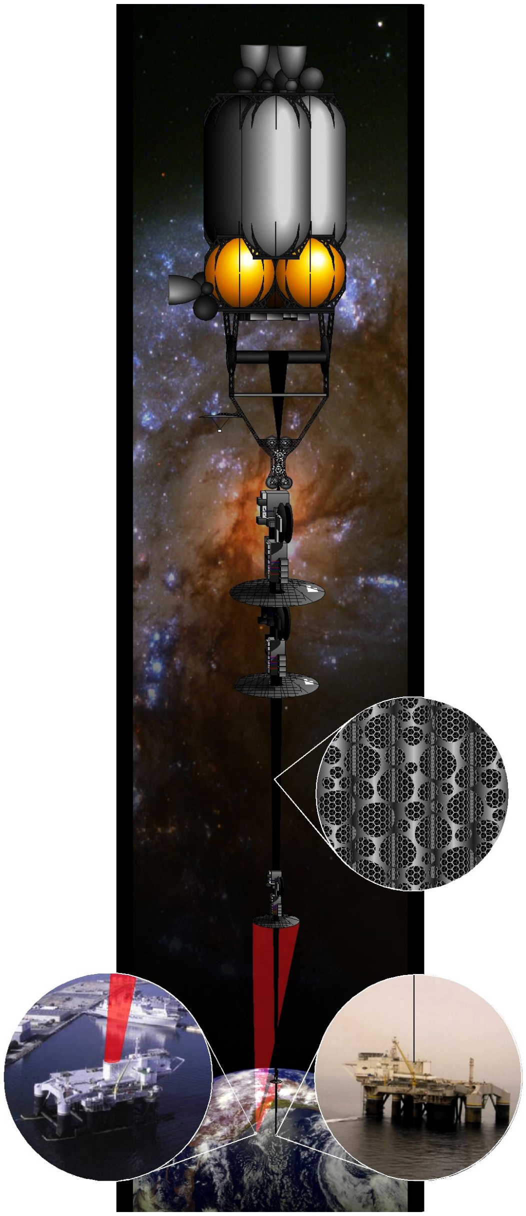
Figure 1: Artist's conception of the space elevator proposed in Edwards, 2000.

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beamed up using a free-electron laser, identical to the one designed by Compower, Inc. and received by GaAs photocells. The spent initial spacecraft and climbers would become counterweights at the space end of the 100,000 km cable. An ocean-going platform based on the current *Sea Launch* program would be used for the Earth anchor. This anchor is mobile and able to move the cable out of the way of low-Earth orbit satellites and storm systems. The anchor location is in the Pacific Ocean, roughly 1500 km west of the Galapagos Islands, to avoid lightning, hurricanes, strong winds, and clouds. The specific cable design would be a curved and tapered ribbon with a width increasing from Earth to geosynchronous and back down to the far end. Deviations in the cable's cross-sectional dimensions would be implemented to reduce the risk of damage from meteors and wind.

In the NIAC report, the proposed first space elevator is estimated to cost $40B and could be financially self-supporting (including recovering the initial construction costs) within the first ten years of operation. The recurring costs are: 1) climbers, 2) power beaming system operation, 3) low-Earth object tracking system operation, and 4) anchor operations. For the initial space elevator these costs could be 1/10th to 1/100th the cost of conventional systems per launch.

If built the first space elevator would be able to launch 13,000 kg payloads every 4 days to geosynchronous orbit or to other planets. The space elevator would allow for the launch of large fragile structures, large solar power satellites, and stations for housing hundreds of individuals. Climbers can be tested easily to ensure reliability and brought back down the cable if there is a problem. The reliability and risk would be more favorable for the space elevator than for any rocket-based launch system. A second generation, larger space elevator would allow for extensive human activities in space including colonization of Earth orbit and Mars. With concentrated effort, the first space elevator could be operational within 15 years depending on technological progress.

2. 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. From strictly an energy standpoint a climber will need 49 MJ/kg of mechanical energy to ascend from Earth to geosynchronous orbit. For a trip of one month this is 19 W/kg average, for one week it is 80 W/kg, for one day it is 561 W/kg and for one hour it is 13,500 W/kg. If the climber is 20,000 kg then the average power needed is 380 kW for a one month trip and 270 MW for a one hour trip. In general terms we would like the fastest trip possible but in the scenario proposed in Edwards[7], a one week travel time or better is required. This one week travel time requirement is due to the susceptibility to the small initial cable to meteor damage. If the climbers are not sent up the cable quick enough to strengthen this first cable then it will be severed. Once the cable reaches roughly 30 width then it is stable and the one week travel time can be relaxed. However, even after the cable is built we want a quick travel time so the cable will be able to operate reasonably both technically and financially. For our discussions we will use a one week travel time and 1000 kg climber (one of the earliest climbers during the construction of the elevator) as a baseline. This will require us to supply 80 kW, plus losses, average power to the climber and results in a preferred power density of roughly 2kW/kg for the power system onboard the climber.

Alternative methods for powering the climbers that have been suggested include: running power up the cable, using nuclear reactors, solar panels, microwave beaming and laser beaming. We will examine the pros and cons of each of these in turn.

Running power up the cable

Carbon nanotubes can be extremely good conductors, comparable to gold. In a composite they will be less conductive but for our discussion let’s assume that the cable can be made as conductive as gold (2e-8Ωm) overall. Two lines, separated by an insulator, will need to run the full length of the cable, 100,000 km. The cable proposed in Edwards, 2000, would have a cross section of 3 mm^2. The resistance of each wire just to geosynchronous would be 100 kΩ. Trying to send electricity across such a resistance would result in 99.5 percent line losses for any conventional use and require a variable voltage from several thousand to several hundred thousand volts. If the line size were increased to 3 cm^2 then the resistance would be 1 kΩ and line losses would be 67% but the total mass of the cable is now 9.2e7 kg. In this case the cable mass is 100 times larger than that proposed in Edwards[7], and would have to be 3 cm^2 in cross sectional area before any climbers could ascend the cable eliminating the possibility of building up the cable size with climbers. Essentially this would require the cable construction at geosynchronous using material already in space (asteroids). If we admit that the cable will be less conductive than this ideal situation then the diameter and mass will increase. The climbers would also need to be designed to use voltages from several thousand to several hundred thousand volts or operations would need to limit the cable to having only one climber on at any time. The last problem with using lines to run power up to climbers is the possibility of one of the lines being cut by a meteor impact. If this were to occur the entire system would be inoperable.

Nuclear reactors

Nuclear reactors are currently massive having power densities of less than 10W/kg. This is well below the 2 kW/kg power densities we will require. Nuclear power also comes with political and environmental problems. In the future they may be a useful power source but at this time they appear to be unusable for our purposes.

Solar Panels

To generate 80kW of power we will need approximately 320 m^2 of solar panels and they will need to be orientated face on to the sun light. A realistic mass for this solar array would be a minimum of 3 kg/ m^2 or 960 kg or a power density of 83 W/kg. This would only leave 40 kg for the remainder of the climber and none for the cable to be carried. If the travel time could be extended to one month then the mass would go down to 240 kg which would leave 760 kg for the rest of the climber and cable.

Microwave Power Beaming

Several studies have been conducted on the beaming of power from space using microwaves[8,9] [Brown, 1992: Glaser, 1992]. The studies were on large space-based solar power statellites in geosynchronous orbit that would beam power to receiver fields on Earth. 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[8,10] [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 _is the wavelength. A low-mass receiving antenna is required so we will select a baseline 3 meter diameter area (A_r =7m^2, 30 kg). We also need 80 kW delivered to an altitude of 15,000 km (for the initial climber, 20 times this for the final climbers) and less to altitudes up to geosynchronous. To deliver this power to our receiver we will need a phased array transmitting antenna of at least 1×10^6 m^2 (1 km^2). Including rectenna (rectifying antenna) efficiency (50%[10,11] [Koert, 1992: Koert, 1999]) and transmission efficiency (30%[10] [Koert, 1992]) we find we will need 2.7×10^5 MW, 1300 MW, and 176 MW, going to the transmitters for 2.4 (λ= 12.5 cm), 35 (λ= 8.6 mm), and 94 (λ= 3.2 mm) GHz respectively for the first climbers. The 2.4 GHz (λ= 12.5 cm) station, using 2.7×10^5 MW of power, or 270 GW, is about 40% of the entire USA electrical generating capacity. A frequency of 94 GHz is definitely 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[11] [Koert, 1999]. The mass of a rectenna would be comparable to lightweight solar panels at 33 kg for a 50 kW receiver[11] [Koert, 1999].

Microwaves at frequencies above 10 GHz are readily absorbed by atmospheric water vapor (easily 50% absorption at 94 GHz) so careful high-altitude or dry site selection is required. High altitude operations are not impossible but do cause numerous difficulties and limitations. First among those limitations is that the cable is not likely to be located at the same sight, since the requirements are quite different. Therefore redundant beaming stations would have to be installed at the cable site to power the climber to altitudes where it would be visible, over the horizon, from the high altitude site.

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 km^2) can be built, a difficult proposition to say the least.

Laser Power Beaming

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 get above a significant fraction of the Earth's atmosphere and thus be able to focus a beam tight enough to efficiently deliver power to a climber. Power beaming from sea level, where we would like to put the cable, is far more practical from an operational point of view. Examining this problem, which is similar to what has been done for adaptive optics work we find that atmosphere distortion is a serious problem. A good treatment of this specific problem can be found in *The Infrared and Electro-Optical Systems Handbook: Atmospheric Propagation of Radiation*[12].

We find that the long-term beam radius is 58 m, which consists of a 57 m short-term beam broadening and a 9.3 m beam wander. The beam will have about 20 times the radius (400 times the area) of a lightweight, 3m diameter receiver, dissipating over 99% of its power elsewhere. To beam up power from sea level we will require adaptive optics or we must live with an efficiency of <0.25%.

Adaptive optics (AO) has been used for a decade or more in large astronomical telescopes such as the 10m Keck telescopes in Hawaii. They have been very successful in eliminating the "twinkle" in star images, the wavering of light as it passes through the atmosphere. From the work of Robert Fugate and others we find that AO has experimentally demonstrated a spatial resolution of 25 cm at 1000 km[13] [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 proposed for 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 the reduced downward acceleration of gravity (~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 astronomical observing. They are currently planning a power beaming demonstration from Earth to a geosynchronous satellite[14] [Lipinski, 1994]. The major problems that hinder the 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 a cooperative client that can be made to retroreflect part of the pump beam or emit a similar kind of tracking beacon. A problem that may arise in our application is thermal blooming of the atmosphere. A 12 m diameter mirror array based on the Hobby-Eberly telescope, is proposed for this application which would result in power densities of 0.44 kW/m^2 to 17.7 kW/m^2. These power densities should not result in thermal blooming of the atmosphere. In addition multiple beaming systems would likely be used which would reduce the power density by a factor of two to four.

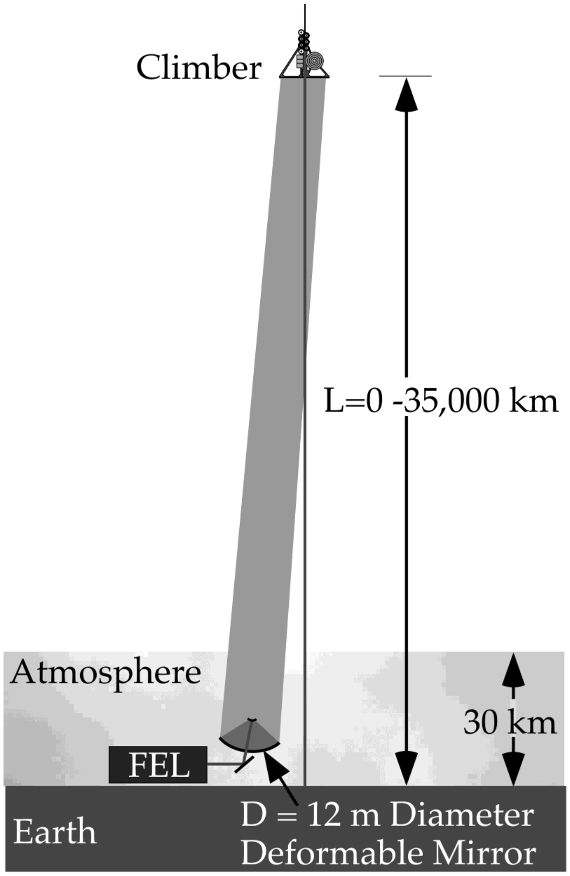

Fig. 1: Illustration of the laser beaming scenario.

The best currently designed system for the Space Elevator concept is the laser designed by Lawrence Berkeley National Laboratory and now waiting to be built[15,16,17] (Bennett 1997a; Bennett 1997b; Bennett 1999). It utilizes the sophisticated room temperature accelerator design built for the Stanford Linear Accelerator Complex (SLAC). The SLAC system at Stanford has been operating continuously for over two years now with great success. The laser designed using this technology will operate at 0.84 μm with an initial output power of 200 kW or more upgradeable to 1,000 kW[18] (Zholentz, 1999).

The complete system will deliver 200 kW (3 picosec pulses every 1 nanosec) into a 7 m diameter spot at geosynchronous. To expand to higher powers multiple identical lasers can be used with their pulses interlaced in time. In the proposed elevator scenario 2.4 MW of power is required so three of the upgraded systems would need to be brought on-line. Recent progress is most encouraging, current tests show 350 kW per wiggler, for a potential full system output of 1.75MW per unit. The efficiency of this system could range from 3 to 30% depending on the operational arrangement.

If the FEL system is selected, the power receivers on the climbers can use specifically designed GaAs photovoltaic cells with 90% conversion efficiency, 90% filling factor and a usable power density of 540 kW/m^2 [19,20] [D'Amato, 1992, and Charlie Chu at Tecstar, private communication].

One additional problem that we need to address is lost transmitting time because of overcast skies. At the proposed anchor location where it would be best to also place the power beaming facility, the percentage of overcast skies appears to be low (figure 2) but to insure continuous operations a additional beaming facilities should be located in separate weather zones. In the proposed situation the beaming facilities could be located on movable ocean platforms within hundreds of kilometers from the anchor. Power beaming systems located in the United States (Mojave desert[21] [Bennett, 2000]) could also be used for supplying power to climbers above 10,000 km.

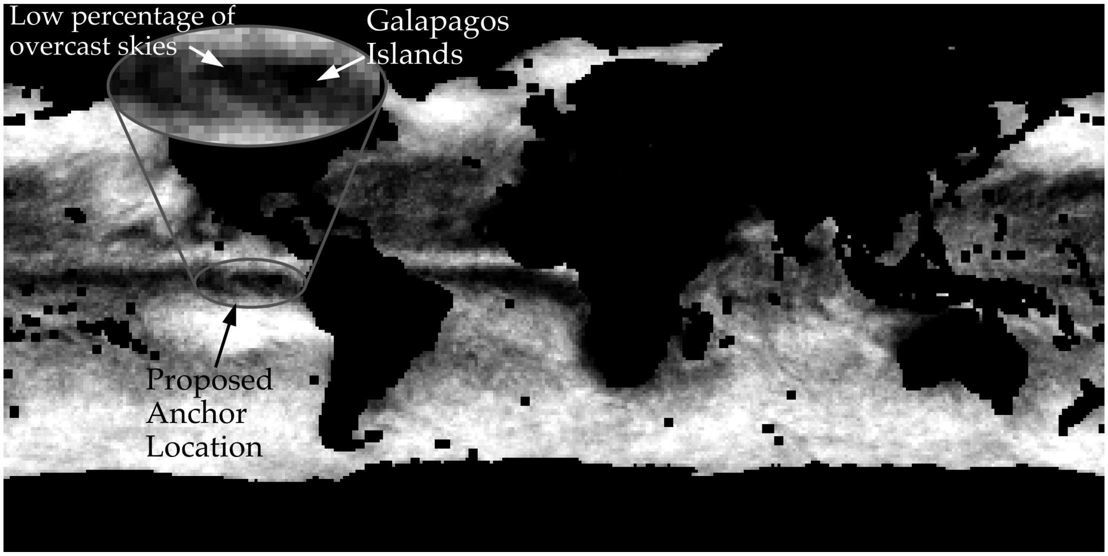

Fig. 2: Cloudiness frequency from satellite microwave data. The dark areas show regions of low frequency of clouds.

3. SUMMARY OF POWER DELIVERY SYSTEMS

Each of the five possible power systems for use with climbers ascending a space elevator are summarized in table 1. For the initial space elevator the laser beaming system appears to be the optimal choice. The simple conductive method of running power up the cable has practical limitations due to the large distances, the desire to use multiple climbers and the single point failure this creates. Nuclear and solar power systems are both too massive for use on a climber. Power beaming using microwaves is a possibility except that it is extremely inefficient in this application and the power generation costs would be extreme. Power beaming using a FEL and adaptive optics would allow for construction of the elevator in an efficient manner, have minimal negative impact on the climber and cable design, be able to supply large amounts of power and the technology is reasonably mature. Its susceptibility to clouds can be overcome with redundant systems. The efficiency, thus the operating cost, of the laser beaming system is comparable or better than the other systems as well[22] (Westling 2001).

Table 1: Summary of power delivery systems

	Advantages	Disadvantages
Conductive	• Simple in concept • Standard technology	• Requires massive cable • Requires complex climbers • Susceptible to catastrophic damage
Nuclear	• High energy density	• Political and environmental problems • Massive
Solar	• Simple • Standard technology	• Low energy density – too massive or too little power
Microwave beaming	• Minimal impact on cable or climber • High power available • Primary system located on Earth	• Requires large area transmitters • Requires transmitter location at high altitude • Inefficient
Laser beaming	• Minimal impact on cable or climber • High power available • Primary system located on Earth • Mature technology	• Susceptible to clouds

4. CONCLUSIONS

The space elevator is a unique system for getting to Earth orbit or to other locations in the solar system. Recent design work has illustrated that the concept is feasible with current or near-future technology. One of the major components of the space elevator is the power delivery system and its selection will impact the rest of the system design. By examining the possible power delivery systems we have found how each will perform and what impact it will have on the space elevator design. Our conclusion is that a laser power beaming system utilizing a Free-Electron Laser and adaptive optics, similar to that designed by Compower, is essentially idea for the first space elevator. Advances in technology may make others systems more viable in the future but with the laser beaming system's current capabilities for delivery of high power at great distances it appears to be the obvious choice for the first system.

ACKNOWLEDGEMENTS

The author would like to thank the NASA Institute of Advanced Concepts for their financial support and encouragement. The author would also like to thank the many colleagues who have made this work possible and specifically Hal Bennett for his assistance on this paper and for discussions on the laser power beaming system.

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