The NIAC Space Elevator Program

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Abstract

The NASA Institute for Advanced Concepts (NIAC) has been supporting a space elevator development program to investigate the initial design, deployment and operations scenario. The work has produced a plan for the construction and operation of a small (20 ton capacity) space elevator within the next couple decades. The elevator cable is composed of a carbon nanotube composite extending 100,000 km from an ocean-going anchor station at Earth to beyond geosynchronous altitude and can be ascended by climbers using a laser power beaming system and an electric motor. All the foreseeable operational hazards have been examined and solutions proposed. This paper will present the Phase I results along with the current Phase II progress. We will cover the design, deployment and operations scenario as well as presenting the recent laboratory tests on cable segments and system simulations.

Introduction

The space elevator first appeared in 1960 (Artsutanov) in a Russian technical journal. In the following years the concept appeared several times in technical journals (Isaacs, 1966; Pearson, 1975; Clarke, 1979) and then began to appear in science fiction (Clarke, 1978; Stanley Robinson, 1993). The simplest explanation of the space elevator concept is that it is a cable with one end attached to the Earth's surface and the other end in space beyond geosynchronous orbit (35,800 km altitude). The competing forces of gravity at the lower end and outward centrifugal acceleration at the farther end keep the cable under tension and stationary over a single position on Earth. This cable, once deployed, can be ascended by mechanical means to Earth orbit. To place a spacecraft in geosynchronous orbit the climber simply ascends to that altitude and releases its payload. To place a spacecraft in any other Earth orbit the payload would require a small engine to achieve the proper orbital velocity. If a climber proceeds to the far end of the cable it would have sufficient energy to escape

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from Earth’s gravity well simply by separating from the cable. The space elevator thus has the capability in theory to provide easy access to Earth orbit and most of the planets in our solar system (Pearson, 1975).

In comparison to many fields of active research there has been little quantitative work done on the space elevator. Pearson and a few others did some quantitative work in the 60’s and 70’s but in recent years the space elevator has been largely ignored in the technical journals. An alternative area of research in sky hooks (a cable between two orbits for orbital transfer) has emerged and produced some interesting work (*Proceedings of the Tether Technology Interchange Meeting*, Huntsville AL, Sept. 1997). Even though the basic ideas are similar, the construction, utility, problems and operations are dramatically different between space elevators and sky hooks. Because of these extensive differences we will not discuss the sky hook here.

Our NIAC Phase I work laid out a detailed description of a possible space elevator program (Edwards, 2000b) filling in the gaps found in Edwards, 2000a. A small, carbon-nanotube-composite cable capable of supporting 495 kg payloads would be deployed from geosynchronous orbit using seven shuttles and liquid- or solid-fuel-based upper stages. Climbers (288) are sent up the initial cable (one every 4 days) adding cables to the first to increase its strength. After 2.3 years a cable capable of supporting 20,000 kg payloads would be complete. The power for the climbers is beamed up using a free-electron laser identical to the one being constructed by Compower and received by photocells. The spent initial spacecraft and climbers would become counterweights at the space end of the 100,000 km long cable. An ocean-going platform based on the current *Sea Launch* program is used for the Earth anchor. This anchor is mobile and able to move the cable out of the way of low-Earth orbit satellites. 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. All of the raw technologies required to construct the space elevator may be ready in 10 years. Carbon nanotubes require the most development but they are now produced in the lab with characteristics close to that needed for construction of a space elevator (see figure 1; Li, 2000; Cheng, 1998; Yu, 2000a; Yu, 2000b). Major risk of damage to the cable comes from meteor impacts and atomic oxygen erosion, both can be mitigated through several methods.

The objective of our NIAC Phase I study was to examine all aspects of the space elevator from the basic design and challenges to the overall system cost. There were a large number of areas to investigate, calculations to be done and problems to solve. The specific results of our Phase I study included:

- Finding a power beaming system using available laser and adaptive optics technologies
- Examining the trade-off between laser-based and millimeter-based power beaming systems

- Designing cables on scales of microns to kilometers to survive the environment and minimize the overall mass.
- Calculating and dealing with wind loading on the cable
- Examining and solving the problem of low-Earth objects impacting on the cable.
- Finding two suppliers of carbon nanotubes and quantifying the current state of technology (see figure 3)
- Examining and solving the atomic oxygen erosion problem
- Finding the optimal anchor location west of the Galapagos islands
- Discussing scenarios where the cable might come down and how to mitigate them
- Quantifying aspects of induced oscillations, radiation damage, and induced electrical currents
- Working out a deployment scenario using current launch systems and technologies that requires only seven shuttles and available upper stages
- Working out the orbital mechanics involved in deploying the initial cable.
- Finding a mobile anchor design based on oil drilling platform technology
- Working out the meteor fluxes and damage rate for our proposed cable
- Working out a cable design that will survive the expected meteor flux
- Examining the current state of spooling technology
- Determining the solar system destinations accessible for different elevator lengths
- Laying out a scenario for deploying a Martian elevator.
- Developing a detailed deployment schedule
- Working out a design for the climbers that fits the mass and power budget
- Laying out various program design options
- Refining the budget estimates for the entire system

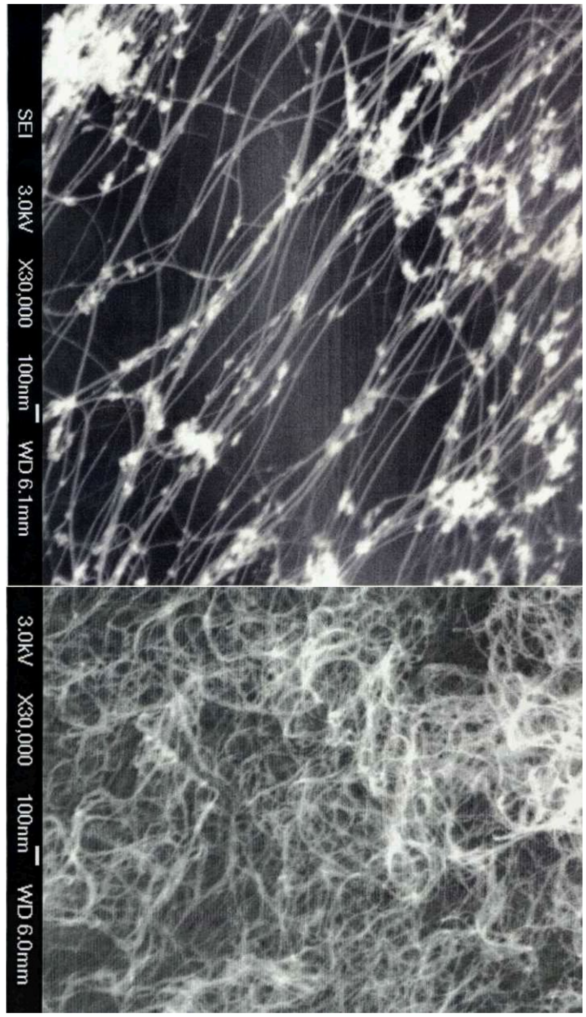

Figure 3: Carbon nanotubes from The Chinese Academy of Science (top panel) and CNI (bottom panel)

The bottom line is that we examined the entire system in detail and found a space elevator design that will work, a method to deploy the cable, and no specific reasons why a space elevator can't be built in the coming decades (10 years after the technology is ready) at a reasonable cost ($40B) and risk. The major hurdle is production of the cable. It was also found that the space elevator will not only be able to be done for less than some current programs but it 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 can be 1/10 to 1/100 the cost of conventional systems per launch. A detailed write-up of our work and conclusions is on the Internet (www.niac.usra.edu/studies/).

As for the utility of the space elevator we found it would enhance our launch capabilities dramatically. Even the first, small cable that we examined (20,000 kg lift capacity every four days) would be able to launch NASA missions to Earth orbit, the moon, Mars, Venus and Jupiter without the launch forces, risk or cost of a conventional system. The space elevator would allow for the launch of large fragile structures such as radio dishes, large diameter mirrors or even extremely long (up to kilometers), rigid booms for interferometry experiments. A second generation, larger space elevator would allow for extensive human activities in space including a geosynchronous station and less risky and less expensive colonization of Mars.

NIAC Phase II Effort

However, our Phase I work did not answer all of the questions. It clearly demonstrated that there are solutions but did little testing of the specific hardware or scenarios we proposed. In Phase II we are concentrating on the details we were unable to address in Phase I and testing the design options. The Phase II work is absolutely critical for future planning and design studies. Our Phase II work will answer any remaining basic feasibility questions, define the critical technologies that require development funding from NASA, quantify the effort required to get the technologies ready, complete a thorough examination of the possible design options, their costs and benefits, and refine the budget estimates for construction of the space elevator.

The primary areas that we will attack in Phase II include:

1. Large-scale nanotube production
1. Cable production
2. Cable design
3. Power beaming system
4. Weather at the anchor site
5. Anchor design
6. Environmental impact
7. Placing payloads in Earth orbit
8. Elevators on other planets
9. Possible tests of system
10. Major design trade-offs
11. Budget estimates
12. Independent review of program

Large-Scale Nanotube Production : To date we have received carbon nanotubes from two suppliers, The Chinese Academy of Sciences and Carbon Nanotechnologies Inc. (CNI). All of the samples were high quality single-walled nanotubes. Some residual metal catalyst and amorphous carbon were present in the as-produced samples and the nanotubes themselves ranged from several microns to unknown lengths of at least many microns. The Chinese samples appeared as semi-aligned bundles whereas the CNI nantubes were omni-directional. In terms of large-scale production CNI has plans to ramp up their production to roughly 10 kg/day by March of 2002 and to 90,000 kg per year by 2005. The strength of these nanotubes is not yet known but initial measurements on the nanotubes from China placed their tensile strength at 22 GPa.

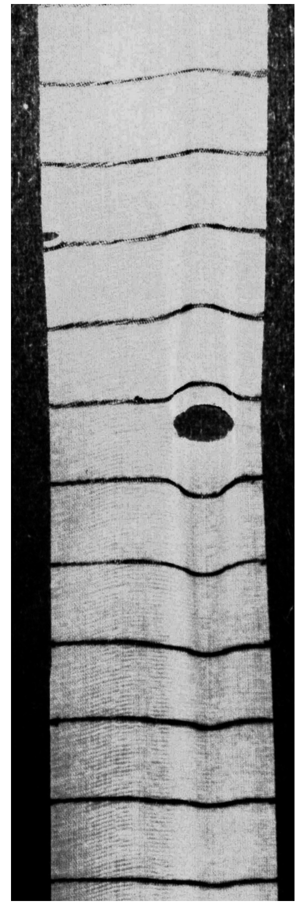

Figure 2: Image of a ribbon placed under tension and then damaged. The hole cut in the ribbon can be seen in the center of the image, Distortions in the ribbon structure are evident in the gridlines above and below the damage. High stress regions are also visible emanating vertically from the left and right ends of the ribbon.

Cable Design: Working with Foster-Miller Corp. we have begun work on producing carbon nanotube composite cable segments that will demonstrate the technology as well as provide material to test for meteor, atomic oxygen and wear resistance.

Initial tests of ribbon designs (not carbon nanotube composites) have been conducted (figure ???) to understand better our specific designs. Finite element analysis of our design has also begun to examine how it will degrade.

Cable Production: The size and critical performance of the cable means that its production will be challenging. The cable length that we are proposing is 100,000 km and its mass is 750,000 kg. Although this in itself sounds daunting, man has constructed many structures of similar size and complexity. The shuttle orbiter is more massive than our first 20,000 ton capacity cable and more complex. Individual cotton gins routinely process 20,000 kg of raw cotton per day, commercial cotton carding (combing and straightening) machines process 720,000 kg per year, and individual cotton spinning machines can produce ~1Mkg of yarn per year (American Textile Consulting). In Phase II we will be using current techniques to put together a cable mass-production plan.

Power Beaming System: The power beaming system we discussed in Phase I utilizes a free-electron laser power source and a set of tuned photovoltaic cells for the power receiver on the climber.

To date we have received photovoltaic cells for examination that should have higher performance than what we baselined. We have also been discussing the laser beaming system with Compower to work out the design and testing of the system.

Weather at Anchor Site: Weather at the anchor station can be a critical hazard. We have acquired data on the lightning rate, wind speed and cloudiness at the proposed anchor location and found each constitutes a minimal problem with our design.

Anchor Design: One of the areas where we were lucky in our Phase I effort was in the anchor design. We found a system in use that has many of the basic characteristics we require in our anchor. The system is the *Sea Launch* ocean-going launch platform. Further examination is underway to insure no problems arrise.

Environmental Impact: In any large program the environmental impact must be considered. We are examining the impact of a catastrophic failure of the cable and how to mitigate this occurrence. If the cable comes down the worst case is that it will burn up on re-entry. The influx of material is small compared to natural infall or our current space operations. The debris will be most likely be large pieces of cable but may include individual nanotubes. Our initial tests show that carbon nanotubes will not dissolve in lung fluids. The next test is to understand the inhalation rate and possibility of damage once inhaled.

Placing Payloads in Earth Orbit: Modeling has shown that the use of a space elevator will be able to save at least 90% of the launch propellant and cost and any Earth orbit can be achieved.

Elevators on Other Planets: An important aspect of any system is its utility. To fully realize the utility of the space elevator we will need elevators not only on Earth but at our destination. This combination of elevators would allow for two-way travel, large-scale exploration and colonization. We have completed conceptual designs and calculations on elevators for Mars, the asteroids, the Moon, and several moons of Jupiter.

Possible Tests of System: We have completed a preliminary design of a feasibility test using a high-altitude balloon, carbon nanotube tether, laser power-beaming system, and prototype climber. We have also examined several other test options .

Major Design Trade-Offs: We have produced a baseline design for the space elevator but realize that many variations on the design are possible. We have compiled various design option along with their cost, impact, advantages and disadvantages.

Budget Estimates: We have worked out budgetary numbers for all aspects of the system and are currently refining and improving on these numbers. We have concentrated on getting costs from existing systems but have also used construction estimates and NASA standard pricing models.

Independent Review of System: To insure the best possible design we have begun to organize independent reviews of our designs. We are organizing a conference for dissemination of ideas and publishing a book on the complete design for use by engineers, scientists and the general public.

Summary

In our NIAC Phase I work we laid out a detailed design for the construction and operation of a space elevator. We included the problems, challenges, hazards and applications. In our NIAC Phase II we are addressing the remaining questions and conducting experimental work to back up the proposed design. Work is progressing as expected and we hope to have answered most if not all remaining questions on the construction of a space elevator by the end of our Phase II in March of 2003.

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