The space elevator: a new tool for space studies

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THE SPACE ELEVATOR: A NEW TOOL FOR SPACE STUDIES

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ABSTRACT

The objective has been to develop a viable scenario for the construction, deployment and operation of a space elevator using current or near future technology. This effort has been primarily a paper study with several experimental tests of specific systems. Computer simulations, engineering designs, literature studies and inclusion of existing programs have been utilized to produce a design for the first space elevator. The results from this effort illustrate a viable design using current and near-term technology for the construction of the first space elevator. The timeline for possible construction is within the coming decades and estimated costs are less than $10 B. The initial elevator would have a 5 ton/day capacity and operating costs near $100/lb for payloads going to any Earth orbit or traveling to the Moon, Mars, Venus or the asteroids. An operational space elevator would allow for larger and much longer-term biological space studies at selectable gravity levels. The high-capacity and low operational cost of this system would also allow for inexpensive searches for life throughout our solar system and the first tests of environmental engineering. This work is supported by a grant from the NASA Institute for Advanced Concepts (NIAC).

Keywords: elevator, transportation

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). More recently, 1999, NASA held a meeting to examine the possible design of a space elevator (Smitherman, 2000). The simplest explanation of the space elevator concept is that it is a ribbon 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 centripetal 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 any Earth orbit or used as a sling to deliver payloads to neighboring planets.

A VIABLE SPACE ELEVATOR DESIGN

Funded by a NASA Institute for Advanced Concepts grant, our program has defined a complete space elevator that can be constructed, deployed and operated using current or near-term technology. In our scenario, shown in Figure 1, an initial ribbon (8 inches wide and on average microns thick) is deployed using four expendable launch vehicles and conventional satellite technology. The initial deployment spacecraft is launched to low-Earth orbit and then assembled. An electric propulsion system raises the

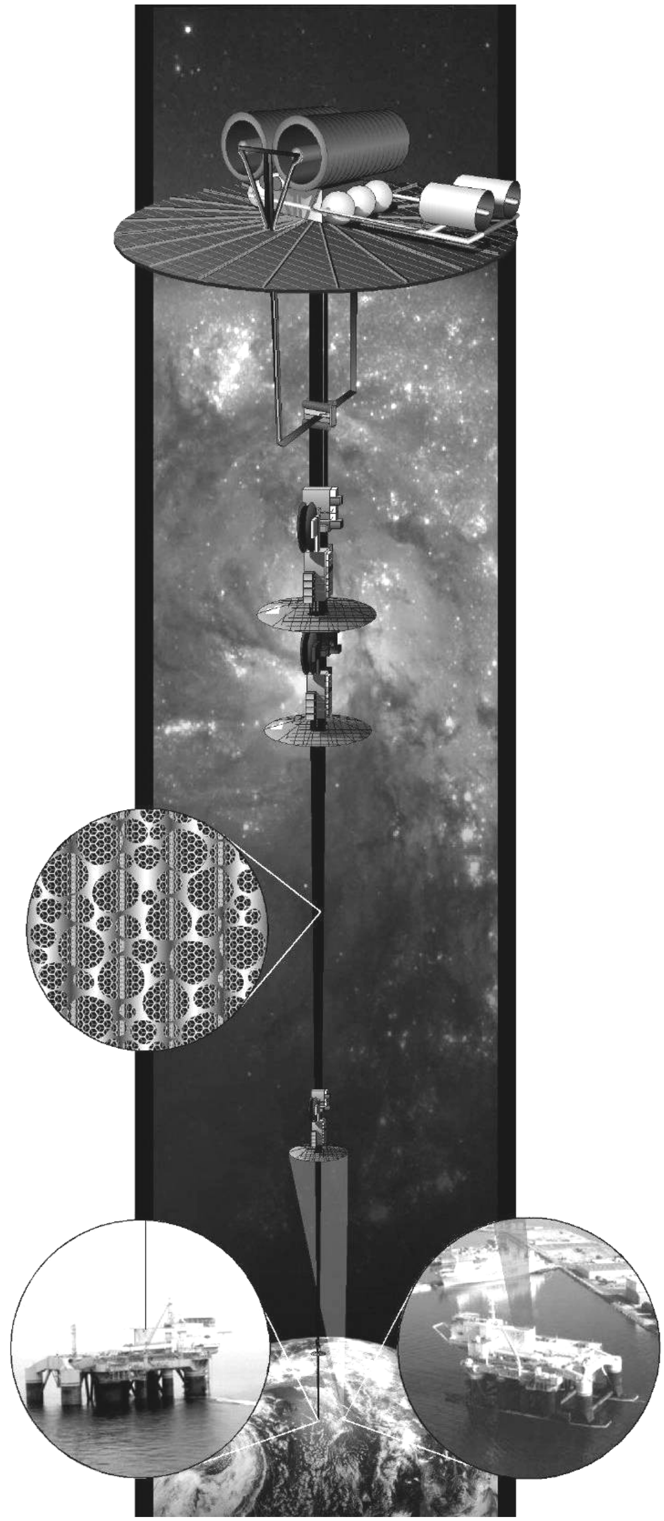

Figure 1. Artist conception of the proposed space elevator.

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orbit of the spacecraft to above geosynchronous where the initial ribbon is deployed back down to Earth. The initial ribbon with one end attached to an anchor platform and the other 100,000 km up in space will be enlarged using mechanical climbers. Each climber will ascend the ribbon and add to it until a complete elevator is achieved. The final system will have a ribbon that is three feet wide and microns thick. The anchor station will be an ocean-going platform located in the eastern equatorial Pacific to avoid lightning, hurricanes, high winds and optimize the ribbon dynamics. Power for the initial spacecraft and the mechanical climbers will be delivered by a laser power beaming system consisting of a free-electron laser and 13 m-diameter, segmented, focusing optic. A debris tracking system will be used to implement active avoidance to deal with the orbital object and debris problem.

The completed system will be capable of carrying 13-ton payloads to any Earth orbit or throwing them to neighboring planets. The total capacity of the system will be roughly 1000 tons (1,000,000 kg) per year at an operating cost of $250/kg (current prices are $10,000/kg to over $100,000/kg). The estimated construction cost is $10 B; it can be operational in 15 years.

The ribbon, being the only basic component of the space elevator not commercially available or in use elsewhere, is the major hurdle in the construction of the space elevator. The sheer length, 100,000 km, is considerable but is well within current technology. The material required for construction of the cable is a carbon nanotube composite. The current state of the art in carbon nanotube composites is the production of kilometers of fibers with several percent by mass carbon nanotube (Andrews, 2003). These fibers have demonstrated the required dispersion and interfacial adhesion near what is required for the space elevator. Additional efforts on the interfacial adhesion and in the fraction of carbon nanotubes in the composite are required prior to construction of the elevator.

The space elevator would allow for the launch of large fragile structures such as solar power satellites to provide clean renewable energy to Earth, commercial manufacturing facilities, inexpensive stations for manned activities, and payloads for exploration and development of space.

The program to date has been funded through $570,000 in grants from the NASA Institute for Advanced Concepts. The effort has defined all of the critical aspects of the design, construction, deployment and operation of the first space elevator. The specific results of our Phase I study (Edwards, 2000) included but are not limited to:

- Finding a power beaming system that will provide the >2 MW of power required.
- Examining the trade-off between laser-based and millimeter-based power beaming.
- Designing cables on all scales from microns to kilometers to survive the environment and minimize overall mass.
- Calculating the cable wind loading and a method to mitigate the problem.
- Examining and finding a solution to the problem of low-Earth objects.
- Examining the atomic oxygen erosion problem and found a possible solution.
- Finding the optimal anchor location.
- Illustrating the possible scenarios in which the space elevator could fall and discussed methods to mitigate the risks and damage.
- Quantifying aspects of induced oscillations, radiation damage, and induced electrical currents to show these are not problems in the scenario we proposed.
- Developing a deployment scenario using current launch systems and technologies.
- 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
- Defining which planetary bodies are 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 options.
- Refining the budget estimates for the entire system and found the space elevator might be constructed for less than some current space programs ($40 B).

Our Phase II effort has refined the Phase I work and has included but not limited to:

- Large-scale nanotube production: Investigating large scale production facilities and techniques as used in textile production such as spooling, quality control, and tensioning techniques.
- Ribbon production: Investigating what aspects of the cable design will affect mass production of the cables we require such as curing times, alignment, and production in mass and in segments.
- Ribbon design: Investigating the ribbon cable design including the interconnect requirements, general design refinement, ribbon testing, splicing techniques, degradation under meteor impacts and atomic oxygen, and modifications to the large-scale profile of the ribbon.
- Power beaming system: Understanding the power beaming system, progress toward construction, difficulties in implementing it on an ocean-going platform and interaction with other system components.
- Weather at the anchor site: Studies of wind, clouds, lightning and hurricanes at the proposed anchor

location and comparison of these results to predicted system performance.

- Anchor design: Completed an initial design study for the anchor platform.
- Environmental impact: Studies primarily concentrate on the health questions related to the infall of severed cables and the ingestion of carbon nanotubes. Initial health studies related to CNTs have been completed.
- Placing payloads in Earth orbit: Quantifying the applicability of the space elevator for placing satellites in all Earth orbits.
- Elevators on other planets: Further defining the applications and enabling aspects of the space elevator.
- Possible tests of system: Laying out the designs, costs and returns of various feasibility tests.
- Completed initial dynamics modeling of the elevator system and found no serious difficulties.
- Major design trade-offs: Examining possible modifications that could improve the overall space elevator system reducing the risk and cost of implementation.
- Budget estimates: Improving the initial cost estimates.
- Independent review of program: Holding a conference and publishing our research results and encourage work in this area.
- Examined legal and regulatory issues related to the space elevator.
- Brought the space elevator concept into the public eye through various media avenues including *Science News, Ad Astra, Wired,* CNN, BBC, the Canadian *National Post,* and over 200 TV, radio and newspaper spots around the world.
- Publishing a book on our completed work (*The Space Elevator,* Edwards 2002).
- Defining the effort yet required prior to construction of the first space elevator.

The result of this continuing effort is illustrating that a space elevator can be built in the near future with current technologies combined with a yet-to-be developed carbon nanotube composite. We have also shown that that the complete development can be completed within two years if sufficient funding is available.

IMPLICATIONS FOR GRAVITATIONAL AND SPACE BIOLOGICAL STUDIES

The space elevator would provide a new level of access to space and allow for more complete studies of biological systems in the environment. Currently, biological systems are placed on rockets and launched into space where they remain for minutes (sounding rockets) to weeks (U.S. Space Shuttle) before returning to Earth. In specific situations the biological study can be conducted in real-time (U.S. Space Shuttle or International Space Station). However, in every case the biological samples are first exposed to increased vibrations in the form of launch forces and limited in size and duration.

With the advent of the International Space Station larger biological samples (up to tens of kilograms) can be used in experiments extending to 90 days. The largest, in terms of mass, and longest duration biological experiment has been humans themselves in space. However, in no case have experiments been able to be conducted on the evolutional affects of the space environment on a species over many generations or modify the gravity in a slow, controlled method of an entire ecosystem over an extended period.

The space elevator is an Earth-to-space transport that will place large payloads in space. Due to the characteristics of the space elevator it is conceivable to have stations or modules located at various altitudes (effectively different gravity levels) along the elevator. For example, an extended study of the affects of Martian gravity can be conducted at an altitude of roughly 4,000 km or lunar gravity at 9,000 km, as shown in Figure 2.

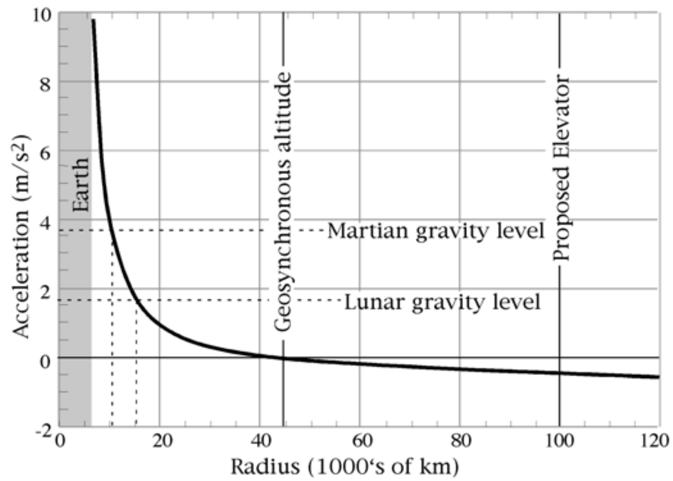

Figure 2. The acceleration felt by a body at specific altitudes along the elevator.

With an operational space elevator entire ecosystems of plants and small animals can be gently lifted intact from Earth gravity to a specified gravity level (0 to 1 *g*). The system experiences no large vibrational spike during the transition. This process also allows a system to be fully operational and stable on Earth, studied for an extended period and then moved to its space environment with a gentle transition. After being placed in orbit, or at the specified gravity level, the ecosystem can be studied through the use of remote cameras for any length of time before being returned with no large vibrational stresses to Earth on the same elevator that placed it in space.

The volume and shape of the payload is also not limited on the space elevator, no hard faring envelop exists on the climbers. A large tubular or spherical enclosure 10's of meters in dimension can be lifted to space as easily as a small cube.

The next level of gravitational and space biological studies is to explore what else exists in our solar system and conduct limited studies on growth of adapted plants and animals in new space and planetary environments.

The proposed space elevator will allow for payloads to be delivered to Earth orbit, Mars, the Moon, Venus or the asteroids for the same cost. A system like this in combination with existing technology will allow for a thorough investigation of our entire solar system, as shown in Figure 3. Complete surveys for existing life can be conducted quickly and inexpensively on all planetary bodies in our solar system. The discovery of life or the lack of life on our neighbors will give clues to the dependencies of life on the environment.

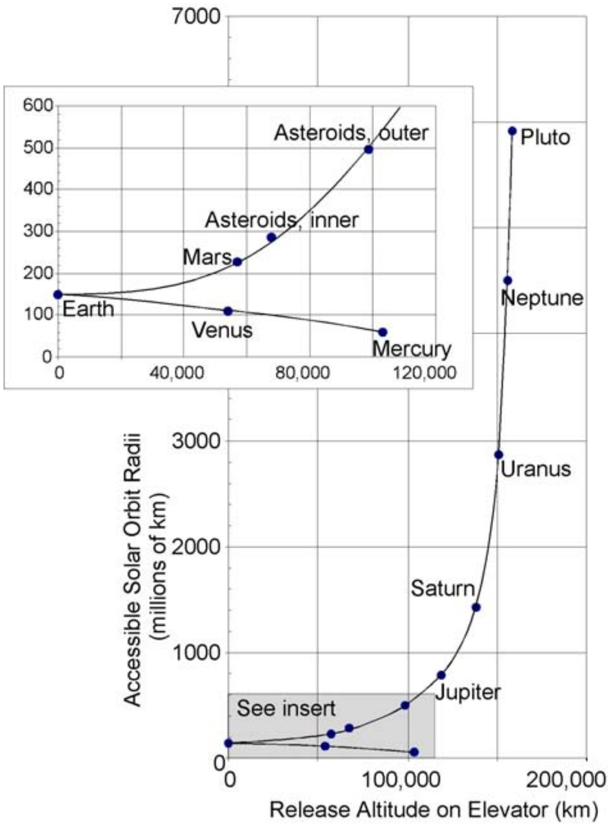

Figure 3. Accessible solar orbits from the space elevator. *The orbits of the planets are marked along with the cable required to access each.*

Proposals for planetary engineering of Mars involve an initial warming stage which utilizes a runaway greenhouse process. Possibilities include large orbital mirrors to warm the poles, changing the absorption with dust, and warming with CFC's. Each requires a substantial mass at Mars. With the first space elevator in operation we will be able to seriously consider each of these proposed scenarios by launching a small test system and a suite of instruments to measure any changes.

For example, ten tons of amorphous carbon could be distributed in a specific area on one of the polar caps. Several tons of instruments can be sent in the same payload to determine the solar heat absorbed by the carbon, transferred to the ice and the amount of greenhouse gas produced. This small scale experiment is large enough to get an understanding of the scenario without creating a large or long-term affect on Mars.

If the initial experiments in environmental engineering are successful and humans decide, after very careful consideration and extensive discussions, that the environment of Mars should be altered then with future generations of elevators, 200 ton or larger payloads, we will also be able to supply the large masses required.

Example Experimental Program

Current biological space experiments, like most space experiments, are often limited in size and duration. If we are successful, the first space elevator will be lifting 13-ton payloads to space every three days or 5-ton payloads to space every day at a fraction of current launch prices. Initial commercial launches could be sold at \$1000/kg to \$2000/kg. Within several years lift prices could be at the \$400/kg level for specific applications. In this scenario a 13-ton (13,000 kg) payload could be placed permanently in a zero gravity environment for \$5 M to \$26 M. Examples of the possible biological programs that can be conducted are below.

<u>Example Program</u>:
We can consider a complete biosphere experiment using a 5-m opaque or semi-transparent sphere with geodesic structure, as shown in Figure 4. The volume of the sphere would be 65 m^3. The mass breakdown and component list for the entire experiment might be:

- One kilowatt power system: 100 kg
- 100 high resolution observing cameras: 200 kg
- Fifty individual diagnostic modules: 500 kg
- Computer processing and associated hardware: 50 kg
- Attitude control system: 1000 kg
- Five-meter diameter, transparent sphere, 5mm thickness: 1020 kg
- Geodesic struts: 50 kg
- Air inside sphere at 1 atm pressure: 55 kg

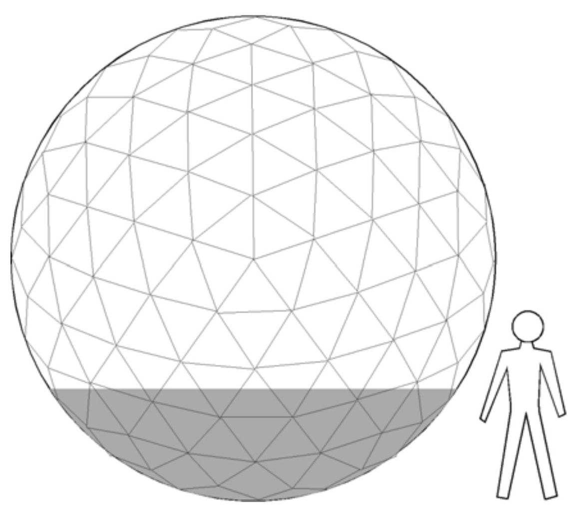

Figure 4. Proposed experiment sphere. *The sphere consists of a semi-transparent sphere with geodesic reinforcing struts. The darker gray region shows the approximate volume of the sphere that can be filled with solid material.*

The support systems have a total mass of 1150 kg. The total mass of the diagnostic hardware is 700 kg. The 5-m diameter sphere and air to fill it is 1125 kg, for a total mass for the hardware of 2975 kg. This allows us just over 10,000 kg of dirt, rocks, water, biomass, plants and animals. This is roughly 10 cubic meters of material or 15 percent of the total 65 cubic meter volume. This design might be ideal for studying the evolution of flying insects or small animals over many generations (years). Examining the growth of larger plants would also work well in a high ratio of free space to useable environmental mass.

One additional item to consider is that the entire system can be brought back down to Earth on the elevator intact after a specified amount of time for in-depth laboratory study of the final configuration.

SUMMARY

The space elevator is under development and could be operational in 15 years. This will allow low-cost Earth-to-space transport and open up opportunities for gravitational and space biology. The larger masses and volumes, the gentler transport, delivery to neighboring planetary bodies, and possible return of completed experiments to Earth allow for many new investigations to be conducted. Two such experiments were discussed: 1) a the large, long-term biosphere for development and environmental studies in a constant low-gravity environment, and 2) planetary engineering studies as a precursor to adaptation of the Martian surface for human use.

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