

CRITICAL TECHNOLOGIES FOR THE DEVELOPMENT OF FUTURE SPACE ELEVATOR SYSTEMS

David V. Smitherman, Jr., Architect
Technical Manager, Advanced Concepts Office
NASA Marshall Space Flight Center, Huntsville, Alabama, USA
E-mail: David.Smitherman@nasa.gov

ABSTRACT:

A space elevator is a tether structure extending through geosynchronous earth orbit (GEO) to the surface of the earth. Its center of mass is in GEO such that it orbits the earth in sync with the earth's rotation. In 2004 and 2005, the NASA Marshall Space Flight Center and the Institute for Scientific Research, Inc. worked under a cooperative agreement to research the feasibility of space elevator systems, and to advance the critical technologies required for the future development of space elevators for earth to orbit transportation. The discovery of carbon nanotubes in the early 1990's was the first indication that it might be possible to develop materials strong enough to make space elevator construction feasible. This report presents an overview of some of the latest NASA sponsored research on space elevator design, and the systems and materials that will be required to make space elevator construction possible. In conclusion, the most critical technology for earth-based space elevators is the successful development of ultra high strength carbon nanotube reinforced composites for ribbon construction in the 100GPa range. In addition, many intermediate technology goals and demonstration missions for the space elevator can provide significant advancements to other spaceflight and terrestrial applications.

INTRODUCTION

During the past year, through a cooperative agreement, the Institute for Scientific Research, Inc., (ISR) in Fairmont, West Virginia, and the NASA Marshall Space Flight Center in Huntsville, Alabama, have been studying a concept for space elevator construction and operations first proposed by Dr. Bradley Edwards through a study grant from the NASA Institute for Advanced Concepts (NIAC) as described in his book *The Space Elevator*¹. The concept proposes deployment of a ribbon, from GEO to the Earth's surface, that would be several meters in width, thinner than a piece of paper, and because of the counter balance mass required, would extend beyond GEO to a total

length of about 100,000km. Its center of mass would be in GEO such that it would orbit the earth in sync with the earth's rotation. Once in place, the structure would be used to deliver payloads from earth to orbit at a cost that could be many times lower than conventional rocket launch systems, and could provide many other benefits by having a much larger capacity, and a more benign launch environment.

The space elevator, being of interest to NASA, has been examined over the years to determine the technologies required, their current state of readiness, and overall feasibility. In 1984, Georg von Tiesenhausen referenced several space elevator concepts in a NASA technical manual, "Tethers in Space: Birth and Growth of a New Avenue to Space Utilization²," speculating what the future of tethers might be beyond the Tethered Satellite System missions that were under development at that time; see Figure 1.

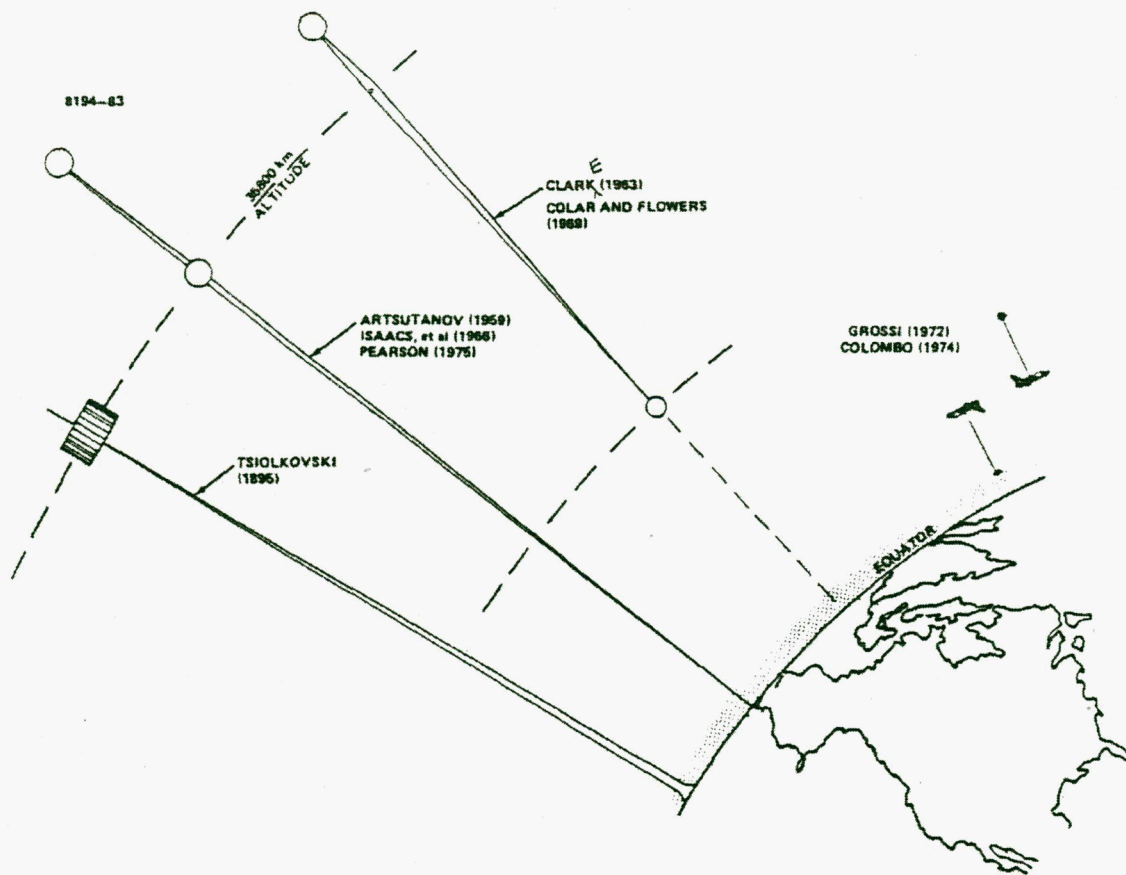


Figure 1: Early orbital tower and skyhook concepts²

In 1999, after many reports on the possible applications of carbon nanotubes, the NASA Marshall Space Flight Center conducted a workshop³ to examine the feasibility of the space elevator concept if a suitable carbon nanotube tether could be developed, and identified many other technologies required and some general design and operational considerations. In the 2000-2002 timeframe, NIAC funded Dr. Bradley Edwards to further examine a new simpler concept for construction of a space elevator utilizing a carbon nanotube composite ribbon and robotic climbers, which represents the baseline concept under study today. And finally, following the NIAC study, NASA and the Institute for Scientific Research, Inc., have conducted this study of the concept. In general, each of these examinations had similar conclusions, in that the overall concept is quite large with many challenges, but if the carbon nanotube composite ribbon material can

be developed, it appears that the other challenges have reasonable technological or operational solutions that can be pursued to make space elevators feasible.

TECHNOLOGY READINESS

NASA often uses a system for ranking technologies called the Technology Readiness Level⁴ (TRL) to help managers make decisions on whether a particular technology of interest should be funded for further development, or is ready for inclusion in a flight program, Figure 2. There are 9 TRL levels, and in general they can be described as TRL 1-2, basic technology research; TRL 3-5, technology development in laboratory experiments and prototypes, and TRL 6-9, integrated systems that are ready for flight. Program managers consider the TRL ranking when examining program risk because they

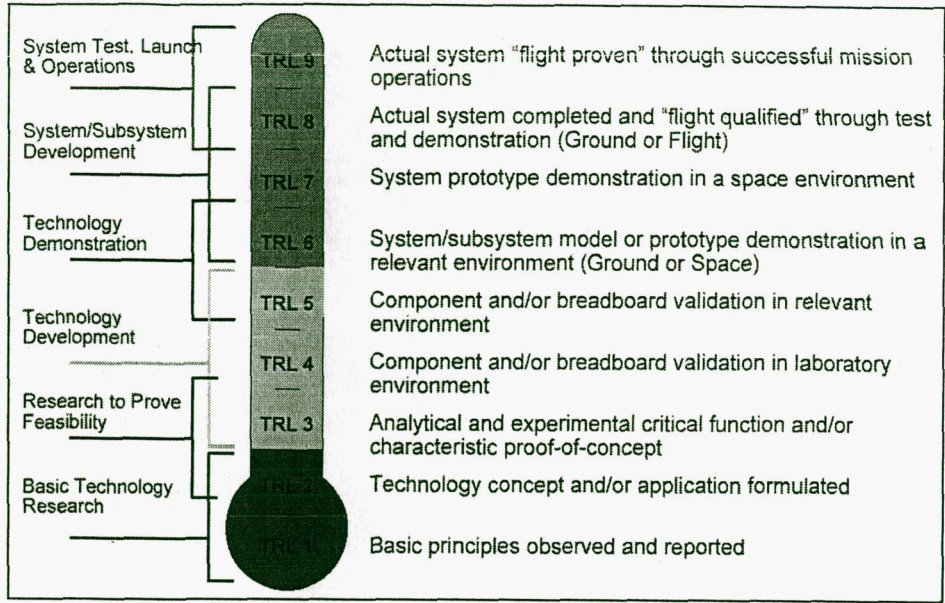


Figure 2: Technology Readiness Level

know that any technology at TRL 5, and lower, brings with it the potential for cost increases and schedule delays if the technology is on the critical path for their program.

TRL Evaluation:

The space elevator is of interest to NASA as a potential future system, but is not a funded program or project because of its low ranking on the TRL scale. In particular, the ribbon material is perhaps the single most critical technology development, which will need to be made of what we now refer to as an ultra high strength carbon nanotube reinforced composite. Stresses in the ribbon have been calculated to be in the 60GPa to 80GPa range with an anticipated strength requirement of at least 100GPa. The carbon nanotube is the primary candidate material that might possibly provide composite constructions in this range with a reported strength above 150GPa. There are many systems in the space elevator that have been examined and ranked on the TRL scale⁵. But, the lowest ranking and perhaps most critical systems that need developing are as follows in the next section.

Low TRL Systems (TRL 1-5):

The following systems have been examined and determined to be at a low TRL and of critical

importance to the development of future space elevator systems. It is important to remember that many of these systems are either already under development in other programs, or could be developed for other purposes that would have broad applications to many space and terrestrial systems in addition to future space elevator developments.

Carbon Nanotube (CNT) Development:

CNT research and development has been in progress for over a decade at many research institutions around the world. Of particular interest is the development of single wall carbon nanotubes because of their ultra high strength characteristics in the 150GPa range. Lacking in this field of research are controlled growth methods that will yield long, aligned, or continuous length tubes, testing and measurement standards for reporting of research findings, and ultimate predictions on potential production rates and cost. These developments will have significant impact on what can or cannot be accomplished in the development of the ultra high strength carbon nanotube reinforced composite ribbon for the space elevator. Because of the successful laboratory experiments to date, CNT technology can be safely labeled at a TRL 4 rating.

CNT Composite Fiber Development:

Ultra high strength CNT reinforced composites development consists of incorporating large quantities of CNT into a suitable composite fiber that will provide overall strength to weight characteristics in the 100GPa range. This will require development of methods for CNT dispersion and alignment in the fiber, bonding between the CNT and the fiber matrix, and a combination of these two that will yield high CNT loading. In addition, the process must be scalable for mass production, be adaptable to surface coatings for protection from the space environment, and be a fiber that is adaptable to fabrication techniques for ribbon construction, splicing, damage repair, and maintenance of fibers and coatings. This technology is perhaps the most important leap for future space elevator development. Because of the difficulties in development of the composite fibers, this technology is still at a TRL 2, where theory and experiments have been attempted without success. The fiber for the ribbon, being the fundamental component of the space elevator, yields an overall system rating of TRL 2 for the earth-based space elevator. It is important to note here, and as will be mentioned later, that space elevators at the moon and other locations do not require this high strength material, and in many cases, are feasible with current materials technology.

Ribbon Design: There are several issues to be examined in the ribbon design once a suitable fiber has been developed. In particular, it should be noted that a single ribbon design of standard width and composition for the full length of the space elevator is unlikely. The ribbon must be designed for the loading and environments it will encounter along its length. Here are some examples of particular interest:

1) Tapered Design: The space elevator ribbon will likely have an average width of about 1 meter. Additional width, perhaps 3 meters, will occur at GEO to accommodate maximum tensile loads, and at low earth orbit (LEO) to withstand the high debris environment. Minimal width, perhaps in the centimeters, is all that may be needed in the atmosphere due to minimal loads, and the need to reduce the ribbons aerodynamic

cross section and thereby help reduce wind loading.

- 2) Tape Sandwich Construction: Several ribbon fabrication methods have been examined, each with particular advantages or disadvantages. The tapped sandwich construction consists of a cross member that keeps vertical fibers in the ribbon properly aligned and will transfer the load from a broken fiber to an adjacent fiber. Alternatives to this approach include woven methods that will transfer loads between fibers as needed.
- 3) Environmental Coatings: The space environment introduces atomic oxygen and radiation that can deteriorate fibers and the composite matrix that binds them together. Coatings will likely be required at appropriate altitudes to protect the ribbon from these effects. Some of these coatings, like nickel to protect carbon fibers from the deteriorating effects of atomic oxygen, could introduce significant additional mass. Detailed design, analysis, fabrications, and testing will be required to find the best engineering solution for these conditions.
- 4) 100GPa Axial Strength: Developing suitable single wall CNT in the 150GPa or greater range is only the first challenge. Once developed, these nanotubes must be incorporated into a fiber that can still yield 100GPa strength even after fabrication and application of all the design variations and coatings along its length to accommodate loading and environmental conditions.

Here again like the fiber, a ribbon of suitable strength has yet to be developed and yields a TRL 2 rating for earth-based space elevator applications.

Robotic Climber Operations: Robotic climbers will be used to construct the ribbon, to conduct inspections and repairs as needed to maintain the structural integrity of the ribbon, and to deliver payloads from the surface of the earth to a geosynchronous altitude, or perhaps other orbital altitudes. The low TRL systems of concern have to do with the amount of ribbon splicing, inspection, and potential repairs required; and the speed with which they need to be accomplished.

- 1) Ribbon Splicing: Ribbon splicing is anticipated as part of the original construction to allow for either a) initial deployment from GEO with additional width added with climbers from the ground, b) deployment from GEO with end to end splicing, or c) repair by splicing additional layers of ribbon over existing damaged ribbon sections. The splicing techniques required for each of these scenarios is different, in that example (a) requires edge splicing, (b) requires end to end splicing, and (c) requires an overlay splicing technique. Speed is of the essence for the edge splicing where additional ribbon will be added full length, 100,000km. The initial conceptual plan was to develop climbers that could do the splicing work at 200km per hour, which would take each climber 21 days to travel the full length of the ribbon. The challenge here is that this splicing operation of nano-scale fibers represents an industrial process that has not been demonstrated in the laboratory. This concern could be alleviated by a construction method using end-to-end splicing of full width ribbons.
- 2) Ribbon Inspection: Inspecting the ribbon for damage and deterioration should be straightforward. The LEO altitudes will require the greatest attention since it is anticipated that there are many objects less than 10cm in diameter that cannot be tracked which could impact and penetrate many ribbon fibers.
- 3) Ribbon Repair Methods: Repairs could include splicing fibers and ribbon sections to replace severed strands, and application of protective coatings. The challenge will be devising a system of repair that will not continue to add mass to the ribbon and thus decrease its payload capacity.

In general, robotic climber development spans the range of TRL 3 to 5, because many of the processes have been done in existing industrial operations, but simply have not been applied or integrated into a robotic climber system. The splicing technique described in 1a above (edge splicing) is probably at TRL 2, but it is worth noting that there are other deployment methods that could eliminate the need for this technology.

Ribbon Control Systems: Ribbon control systems will be required to keep the ribbon in its geosynchronous orbital slot, and control tension, induced waves, climber dynamics, and atmospheric effects. Control systems will likely include base maneuvering, tension reels at the base station, counterbalance thrust control, and possibly a thrust control spacecraft at the geosynchronous altitude.

- 1) Tension Control: Tension control will be required to help control overall dynamics of the ribbon, and to prevent the ribbon from exceeding its maximum designed loading. A properly designed ribbon would be tapered with its maximum width or density at GEO such that tensile loads can be maintained around 67GPa throughout the full length of the ribbon. It is anticipated that loads will vary from induced waves and climber effects, but can be controlled by releasing and retracting ribbon at the base station.
- 2) Induced Wave Control: Induced wave control will be required to counteract climber dynamics and object avoidance maneuvers. When an induced wave is used for object avoidance, a second wave may be required to counteract the first. The effects on ribbon tension and wave tracking can become quite complex.
- 3) Climber Dynamics: Climbers will produce dynamic effects on the ribbon as it climbs due primarily to the change in angular momentum imparted on the ribbon by the climber. The mass and tension in the ribbon will have to absorb the changing angular velocity of the climber as it climbs higher and the ribbon pulls it into higher orbital velocities. If the mass of the ribbon can not absorb this energy through increased tension then thrusters on the climbers may be required, adding additional complexity to the system.
- 4) Atmospheric Effects: High wind speed at lower altitudes can pull the ribbon and low altitude climbers down if the ribbon is not properly designed for these aerodynamic effects and proper tension in the system is not maintained. Control of the lower altitude sections in the atmosphere may require additional systems such as airships

or balloons in the upper atmosphere to carry part of the load for the atmospheric sections, and assist in wave control and object avoidance on the overall ribbon.

Ribbon control is only at an analytical stage of development, and is being studied through a computer model program developed by NASA for the Space Shuttle's Tethered Satellite Systems (TSS) missions. This activity using the General Tethered Object Simulation System (GTOSS) tends to indicate that ribbon control systems are at about a TRL 2 to TRL 3 rating.

Power Systems: There may be several alternatives for power systems for the climbers that have yet to be explored. The baseline concept uses laser power beamed from a ground station up to the climber to produce electricity for the climber's electric motors. This technology has been demonstrated on the ground, but the development and demonstration of a high-powered laser that can track a climber up to 100,000km altitude has yet to be developed, implying that this technology is at a TRL 4. Other alternatives could include nuclear systems, solar arrays and batteries, or development of an electrical conductor in the ribbon for transmitting power directly to the climbers. All of these approaches may be possible, but no detailed analysis or experimental development has been carried out to determine the most practical means for the climber power system.

Tracking Systems: Tracking systems, and the models for predicting the orbits of tracked objects, have been in existence for several decades. The problem for the space elevator is the degree of accuracy required. Current systems in place by the U.S. Air Force Strategic Command were designed to track incoming nuclear missiles. The byproduct of this system through incremental improvements is the ability to track satellites and orbital debris. But, there are several vexing problems with the current capabilities. First, the current system only tracks objects 10cm in diameter or larger; and second, the orbital perturbations are such that an object may come over the horizon several kilometers off from where current models predict. Any object predicted to come

within 10km of the *International Space Station (ISS)* is carefully tracked and analyzed to determine the risk of impact and consideration given to possible maneuvering to avoid the hazard. On the space elevator, a 10km clear zone would sweep through thousands of objects in LEO per year, making the maneuvering task very difficult if not impossible. For this reason, a more precise tracking and prediction system will be required to reduce the clear zone down from kilometers to meters in diameter. Here, the need for more tracking stations yields a TRL 7 for tracking systems, where as the development of perturbation models to predict the orbital track of oncoming objects is of unknown complexity and yields perhaps a TRL 4 rating.

CURRENT ACTIVITIES

Several activities have been in progress over the past year at NASA, ISR, and their support contractors on research and technology development to address the low TRL concerns described above. Of particular interest are the following:

Materials Research & Development:

The Center for Applied Energy Research (CAER) at the University of Kentucky, in Lexington, Kentucky, has developed a process in-house to produce multi-wall CNT and incorporate them into a pitch-based fiber. Research has focused on development of the spin line process that will align the tubes in the fibers and produce continuous multiple fibers in a single run. Once in place the spin line will be used to incorporate other multi-wall and single-wall CNT from other sources to produce higher strength fibers for further research, analysis and testing. The set-up will allow CNT researchers to experiment with incorporation of their products into a fiber, and will allow potential manufacturers of fibers to experiment with production techniques for full-scale manufacturing.⁶

Ribbon Design:

Ribbon design and analysis is being conducted at ISR to determine an optimal approach to a ribbon that can be both lightweight and transfer

load from severed fibers to adjacent fibers⁷. Although the actual fiber is not yet developed, there is sufficient data available that can be applied to finite element analysis programs to model how the ribbon will react given appropriate design elements, materials properties, and constraints. In addition, a competitive approach is also in progress that may yield results for ribbon development as described in the next section on robotic climbers.

Robotic Climber Development:

Robotic climber development is important but was not a primary area of interest for the NASA / ISR activity since this is an area where industry already has significant related activities. Of interest though is the NASA Centennial Challenges grant that was recently awarded to the Spaceward Foundation to conduct tether strength and climber competition challenges. This competitive program is anticipated to produce ongoing interest in the space elevator concept and develop new systems that will advance the technology for robotic climber systems, beamed power systems, ribbon design, and space elevator development in general.⁸

Space Elevator Dynamics Modeling:

In the 1980's NASA developed the GTOSS to model the tether dynamics of the tethered satellite missions, TSS-1, and TSS-1R, flown from the space shuttle. This program has been updated to accommodate space elevator sized tethers to study the dynamics of the space elevator and the various modes of operation such as ribbon deployment, climber dynamics, atmospheric dynamics, and induced waves for object avoidance.^{9, 10}

Tracking & Object Avoidance Simulations:

Tracking and object avoidance activities have included use of Satellite Tool Kit (STK), the STRATCOM satellite tracking system from the U.S. Air Force Strategic Command, and model data from the GTOSS program described above. These tools have made it possible to study an approach to object avoidance by moving the base station and by inducing a wave in the ribbon timed to propagate up the ribbon for object avoidance.¹¹

The current NASA / ISR cooperative agreement will be active through the end of this calendar year. Summaries of current findings from these activities are available in the papers referenced above, and final results will be available in a final report on the NASA / ISR cooperative agreement to be released next year.

FUTURE NEEDS

As indicated above, there are numerous technologies and systems that will need further research and technology development in order to move forward on a space elevator. A way to capture and integrate these technologies is through definition of ground and spaceflight demonstrations that could be done to prepare the way for space elevator development and complimentary missions. These are the types of demonstration projects that are often laid out on a roadmap, or milestone chart, showing progressively more complex developments leading toward an ultimate goal. The following section on Future Needs, are some preliminary thoughts on how such a technology development roadmap for the space elevator might be formulated.

Ground Tests:

There are several developments that need to be accomplished in the laboratories and in ground systems tests before spaceflight tests will be productive. These include Materials Development, Materials Testing in a Relevant Environment, Vertical Treadmill Tests, and Tethered Balloon Tests.

Materials Development & Testing in a Relevant Environment: Materials development has been discussed in previous sections noting the need for further development of ultra high strength CNT reinforced composites. In addition to that development, the composite fibers must be incorporated into a ribbon designed to withstand the loads and environmental conditions in which it will be subjected. This will include space environments tests in vacuum, and under simulated conditions for debris impacts, and exposure to radiation, atomic oxygen, and the full range of

atmospheric conditions at the lower end. These tests will lead toward appropriate tether design for each section which will likely include changes in width and density to accommodate loading, debris impacts, and atmospheric winds; and changes in protective coatings for sections exposed to high radiation and atomic oxygen environments. Once a suitable design is in place for each section of the ribbon then development and testing of maintenance climbers can be done on vertical treadmill tests.

Vertical Treadmill Test: The space elevator can be divided up into four sections based on the environments that each section will encounter. Some of these sections overlap based on the multiple environmental conditions in each section. Here is a summary that should help explain the ribbon design and the climber maintenance requirements that would be developed and tested on a vertical treadmill test for each section.

- 1) Micrometeoroid Impacts: The longest ribbon section would fall under this category of testing extending from LEO up to the counter weight at 100,000km altitude. Ribbon density would vary to accommodate maximum loads at GEO, but it is thought the width could be a consistent 1-meter, and survive the micrometeoroid impacts for 10 years without repairs. The task for the climber tests would be to make inspections along this type ribbon and make appropriate repairs to broken fiber strands to maintain the ribbon's structural integrity and thus extend its life. When a strand is broken the ribbon is designed with taped or woven cross-links that transfer the load to adjacent strands. So, key to the repair operations will be devising a method to identify the broken strands, weave in a splice, and reload the repaired area.
- 2) LEO Objects and Debris: LEO objects have been the subject of object avoidance to avoid damage to the space elevator and active satellites. In addition, there is thought to be many thousands of debris below 10cm in diameter that cannot be tracked with current systems. An approach to this problem is to expand the width of the ribbon from 1-meter to about 3-meters to survive

more impacts with larger objects up to 10cm in size. Here the climber would have to accommodate a wider cross-section for inspections and repairs; and, although the repair work would be similar to the upper section described above, it could involve repairs to many more strands at each point of impact.

- 3) Radiation & Atomic Oxygen: The ribbon materials will have to survive the vacuum and radiation environments of space along its entire length above the atmosphere, but of particular concern is the atomic oxygen in LEO. Metallic coatings may be required to protect the composite fibers in the ribbon from deterioration. Here, the climbers will need an inspection capability to examine the coatings and make coating repairs as needed. Also of concern is the wear on coatings from the climber traction wheels.
- 4) Atmospheric Conditions: The last few hundred kilometers enters the earth's atmosphere with a variety of effects from wind, moisture, and lightning. Of particular concern is the cross-sectional area of the ribbon and its reaction to wind driven forces. It has been found that a 1-meter wide ribbon in the atmosphere can cause a significant force that will elongate, or pull part of the space elevator down into the atmosphere⁹. To avoid wind driven problems the cross-sectional area could be reduced to something more like a rope than a ribbon, and could be supported by balloons or airships in the upper atmosphere if needed. In either case, the climbers will likely have a different role that will require inspections of the rope like section at the lower end and then splicing in a replacement section when significant wear or damage is found.

Tethered Balloon Tests: The idea behind a tethered balloon test is to build prototype sections of the space elevator ribbon and suspend them from a balloon or airship in the upper atmosphere and do a full systems test of the climbers, their robotic functions, the beamed energy system that powers the climbers as they traverse the ribbon from the ground up to the balloon, and to test overall ribbon deployment and control systems. These tests

would likely include climbers for ribbon inspection, maintenance of coatings, repair to severed fibers, and splicing; and climbers with payload delivery systems.

Spaceflight Tests & Demonstrations:

Several flight tests have been conducted on tether systems with varying degrees of success. As seen in the two tethered satellite missions there are unexpected events that can occur and result in deployment mechanisms locking up or static electricity discharge resulting in a severed tether. To avoid such events on a system as large as a space elevator it will be important to conduct spaceflight tests to develop and demonstrate quality systems that will not fail. In this section we will examine progressively more complex spaceflight experiments in LEO, GEO, and at the moon, to demonstrate space elevator deployment and control leading up to the development and deployment of an earth based space elevator.

LEO Deployment Demonstration:

There are perhaps many approaches to demonstration missions in LEO that could satisfy requirements of space elevator deployment testing. The interest here is to demonstrate deployment of a tether down from a primary spacecraft with an end effector spacecraft in a gravity gradient stabilized orbit. This would seem like a simple demonstration, but it is important to remember that in the space shuttle TSS missions, neither flight reached full deployment of the tether. New deployment and control tests could be done with a free flying spacecraft or as part of a payload from the space station. Figure 3 shows an interesting advanced concept for the space station using an electrodynamics tether for propulsion. This type of project would significantly advance the technology for tether deployment and control in space. The benefits for the *ISS* include a propellant-less propulsion system providing reboost through electrodynamics, and if desirable in the future, a system that can relocate the space station to a lower inclination for use in future lunar mission architectures. The risks for this system include the possibility of a severed tether and its entanglement with other components on the *ISS*.

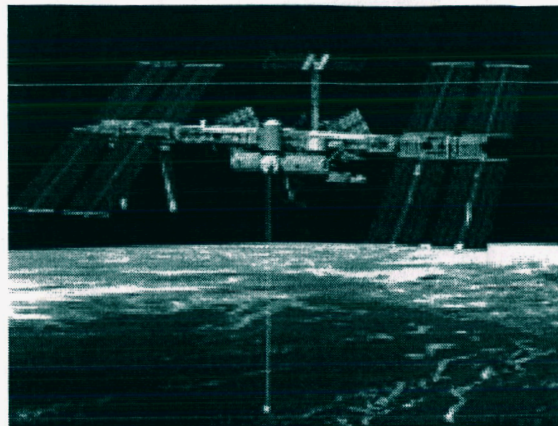


Figure 3: *ISS* concept for an attached tether using electrodynamics for propulsion

Another system of interest that is quite large is the concept for a LEO space elevator, Figure 4, sometimes called a "Bridge to Space" that uses a LEO tether several thousand kilometers in length to lift payloads into a GEO transfer orbit (GTO). This concept would have to address orbital debris and object avoidance requirements similar to those of a full-scale space elevator. So, this type of system might be a good precursor for space elevator technology development. It operates by payloads delivered to the lower end from a suborbital vehicle, and then released at the upper end into a GTO trajectory. Such a system would significantly reduce the requirements on both the launch vehicle and the upper-stage.

GEO Deployment & Traversing Demonstration: The next major demonstration mission should probably be done at GEO to demonstrate tether deployment and control of hundreds, or perhaps 1000's of kilometers in length. In addition, a climber traversing this tether would be of interest as part of the demonstration to observe control issues, conduct inspections, and make repairs. Like the LEO space elevator and *ISS* tether mentioned above, there are applications for this type of tether that could be developed. They include: 1) a geosynchronous communications satellite with a split power bus and transmitter; and, 2) a LEO to GEO space elevator.

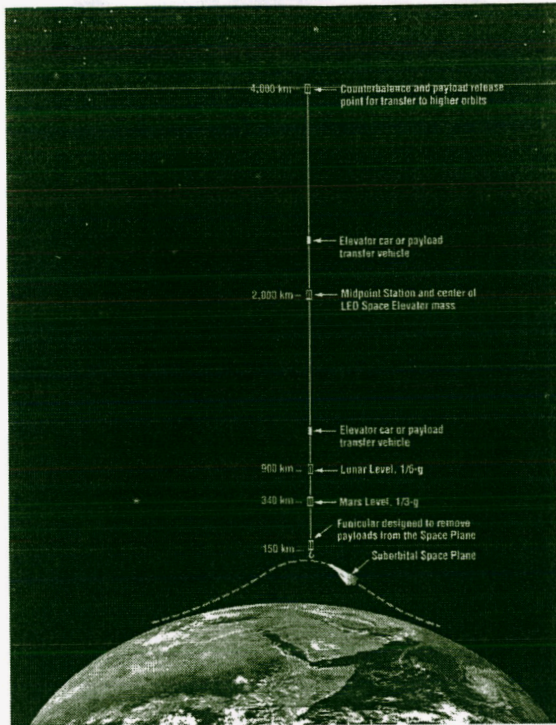


Figure 4: A LEO space elevator, or “Bridge to Space” concept by the Lockheed Martin Company.¹²

- 1) Geosynchronous Communications Satellite: A geosynchronous satellite with the power system bus at the upper end, and the transmitter suspended at the lower end in a MEO or LEO altitude could significantly reduce the lag time for two-way communications and thereby expand the utility of GEO satellites for telephone communications.

- 2) LEO to GEO Space Elevator: This elevator would be similar to the LEO space elevator described above and shown in Figure 4, except that it would be designed to hoist payloads directly from LEO to GEO, and could release payloads beyond GEO for delivery to the Moon, Mars, or other interplanetary destinations.

Full Scale Lunar Demonstration: Lunar space elevators, or lunar towers as they are called in Figure 5, are possible at the earth-moon L1 & L2 points. These structures are of interest as part of a transportation infrastructure at the moon, and as a full-scale demonstration of space elevator construction, control, and operations. The length of a lunar space elevator would be about the same as an earth-based space elevator, but would not require material strengths as high due to the lower gravitational effects. Lunar space elevators have been studied before, and are being studied again under a NIAC grant.^{13, 14}

Figure 5 provides a summary of the space elevator related operational systems that could be developed around the earth and the moon that could eventually lead to full-scale development of an earth-based space elevator. All of the tether concepts mentioned in this section, except for the earth-based space elevator, appear to be possible to construct with current materials technology.

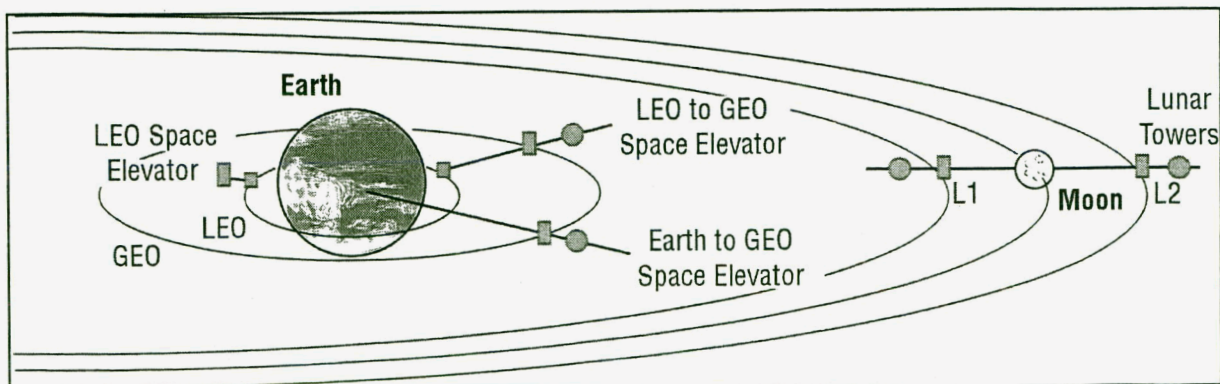


Figure 5: Concepts for space elevators around the Earth and Moon.

CONCLUSIONS

In conclusion, the most critical technology for earth-based space elevators is the successful development of ultra high strength carbon nanotube reinforced composites for ribbon construction. Since this material is the critical item that will make space elevators at earth possible, the space elevator along with the ultra high strength carbon nanotube reinforced composite material is at a TRL 2 rating. Once ribbon material strengths above the 67GPa range are demonstrated to a higher TRL 6 level, then practical plans for demonstration and construction of an earth-based space elevator system will be possible. In the mean time, there are other demonstrations and practical projects using tethers in LEO, GEO and at the moon that could be investigated further for their own merit. In addition, many intermediate technology goals and demonstration missions for the space elevator can provide significant advancements to other space flight and terrestrial applications.

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