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TECHNOLOGY DEVELOPMENT AND DEMONSTRATION CONCEPTS FOR THE SPACE ELEVATOR

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

ABSTRACT

In 1999, the author managed for the National Aeronautics and Space Administration (NASA), a space elevator workshop at the NASA Marshall Space Flight Center to explore the potential feasibility of space elevators in the 21st century, and to identify the critical technologies and demonstration missions needed to make the development of space elevators feasible. Since that time, a NASA Institute for Advanced Concepts (NIAC) funded study proposed a simpler concept for the first space elevator system using more near-term technologies. This paper will review some of the latest ideas for space elevator development, the critical technologies required, and some of the ideas proposed for demonstrating the feasibility for full-scale development of an Earth to Geostationary Earth Orbit (GEO) Space Elevator. In conclusion, this paper finds that the most critical technologies for an earth-based space elevator include Carbon Nano-Tube (CNT) composite materials development and object avoidance technologies; that the lack of successful development of these technologies need not preclude continued development of space elevator systems in general; and that the critical technologies required for the earth-based space elevator are not required for similar systems at the Moon, and other locations.

BACKGROUND

In the 1990's, advances were made by several researchers indicating that carbon nano-tubes might be the high strength material needed for fabrication of space elevators from geostationary orbit down to the surface of the Earth. These findings have led to the continued development of nano-tubes for structural applications and serious investigations into the space elevator concept as a potential infrastructure element for space science missions, human space exploration, and commercial space development.

NASA Study:

To investigate this possibility the author, in 1999, managed for NASA a space elevator workshop at the NASA Marshall Space Flight Center in Huntsville, Alabama, to explore the potential feasibility of space elevators in the 21st century, and to identify the critical technologies and demonstration missions needed to make development of space elevators feasible.[1] Specifically, this study identified CNT composites, tether demonstration missions, tall tower construction technology, electromagnetic propulsion, and space infrastructure development in general as major technology developments required before a space elevator could be developed. The time frame for possible space elevator

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construction was assumed to be greater than 50 years—in the latter half of the 21st Century.

NIAC Study:
Since that time, a NIAC funded study of the Space Elevator proposed a concept for a simpler system using more near-term technologies.[2] Not required were the former findings for tall tower construction technology, electromagnetic propulsion, or extensive space infrastructure development. Instead, this simpler approach used more near-term technologies including CNT composite ribbon development, electric propulsion, wireless power transmission, mechanical crawlers, and collision avoidance systems. In addition, the NIAC study resulted in a book "The Space Elevator"[3] that provides a good detailed description of the concept and the economics of the space elevator from a business perspective. The premise of this study was that the space elevator can be built with more near-term technologies that may make construction possible in the first half of this century—perhaps as early as 15 years away.

Current Activities:
As a result of these studies, serious interest in the space elevator as a potential future space infrastructure element has grown in both technical, public, and private circles. In 2004, NASA and the Institute for Scientific Research established a cooperative agreement to conduct further investigations into the space elevator concept. Specific investigations to be conducted include a more detailed systems engineering study of the entire concept, continued development of the high strength CNT composite materials, ribbon dynamics analysis for a full length space elevator structure including control systems concepts for object avoidance, ribbon design, prototype climbers, and collection and production of technical papers and educational materials on the space elevator for the technical community and the general public.

In light of the prior studies, and the current activities, this paper will review some of the latest ideas for space elevator development, the critical technologies required, and some of the ideas proposed for demonstrating their feasibility.

CRITICAL TECHNOLOGIES

NASA's approach to developing new space systems for future deployment includes the identification of all critical technologies by ranking their level of maturity on a scale known as a Technology Readiness Level (TRL), Figure 1. This approach makes it easy for technologist to identify the technologies that need to be funded for continued development, as well as providing an overall gauge for project managers as to the likelihood that the project is ready, or not ready, for full scale development.

Technology Readiness Levels:
Basic Technology Research comprises TRL 1: Basic principles observed and reported; and TRL 2: Technology concept and/or application formulated. The CNT composite ribbon development is probably in the TRL 2 category because the CNT has been observed to have the required strength at the nano-scale, but large-scale composite fibers have yet to be developed with the required strength for construction of a space elevator. Since the ribbon structure is the primary component of the space elevator, and there are no know substitutes, the entire system for Earth to GEO applications is considered an advanced concept worthy of study and technology development, but not far enough along to warrant major project funding. In other words, there is no guarantee that adequate time and money will mature this technology. Note also the red color coding, indicating that critical technologies at this level should not yet be counted on for near-term projects.

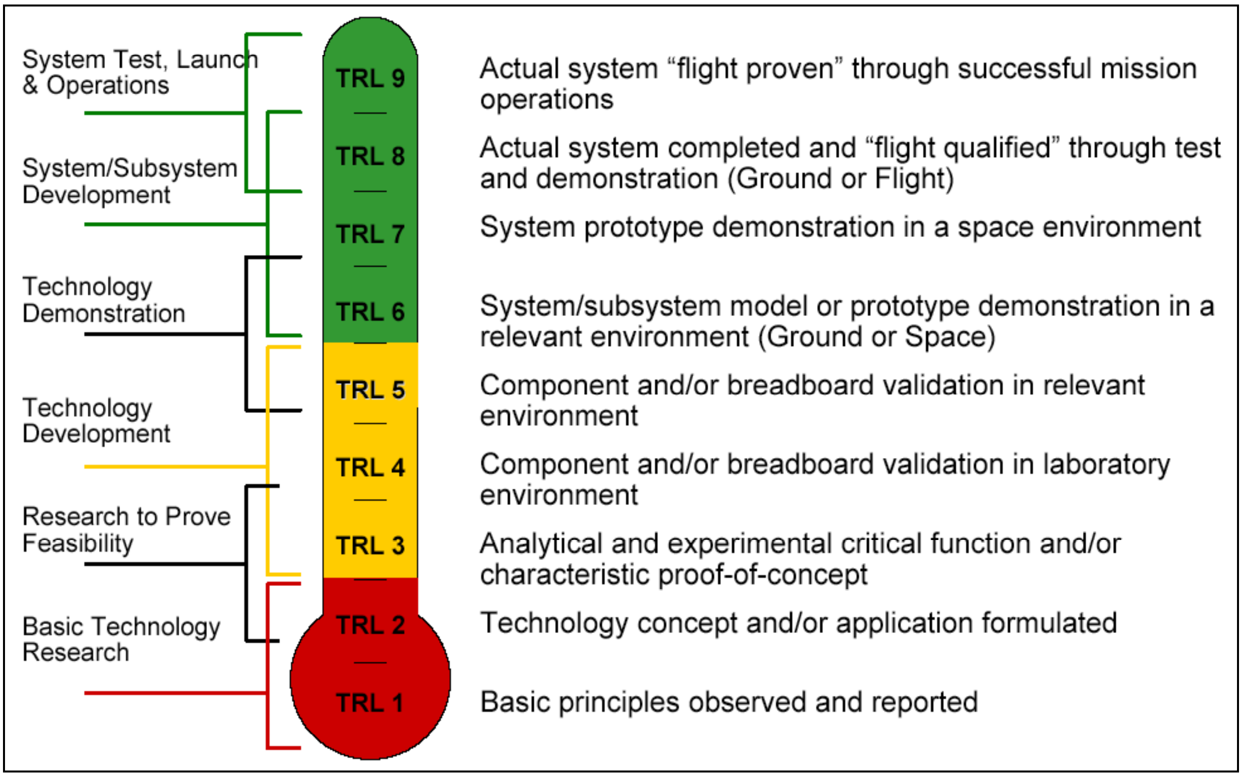


Figure 1: Technology Readiness Level

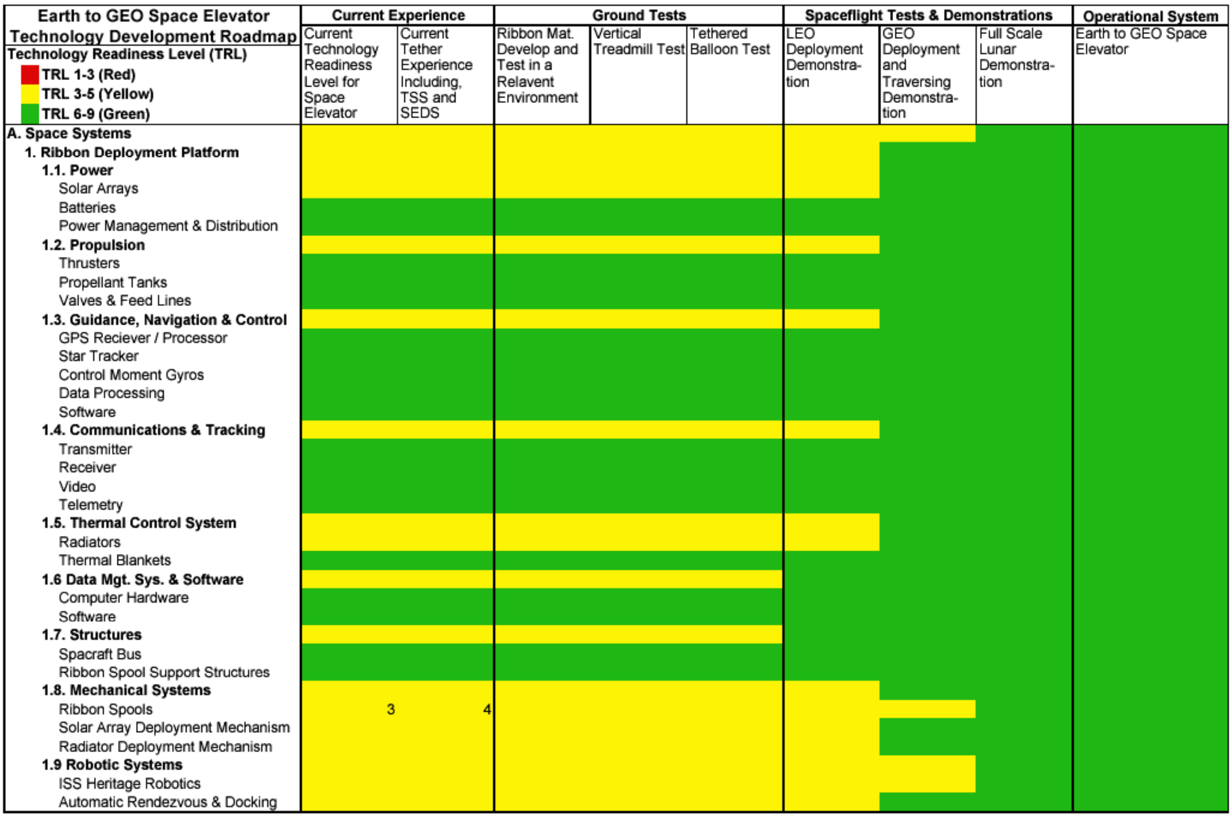
Technology Development comprises TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept; TRL 4: Component and/or breadboard validation in laboratory environment; and TRL 5: Component and/or breadboard validation in relevant environment. Many of the mechanical systems for the space elevator fit into these categories, in that similar mechanisms exist, but have never been put into the configurations required for the space elevator, and/or have never flown in a space environment. All required technologies in these categories are assumed to be mature enough that they could be developed for the project given enough time and money. Hence, the yellow color could be interpreted as proceed with caution.

System/Subsystem Development comprises TRL 6: System/subsystem model or prototype demonstration in a relevant environment (Ground or Space); TRL 7: System prototype demonstration in a space environment; TRL 8: Actual system completed and "flight qualified" through test and demonstration (Ground or Flight); and TRL 9: Actual system "flight proven" through successful mission operations. Some of the tether deployment hardware, spacecraft systems, and ground stations fit into these categories because similar systems have flown on previous space missions, or have been tested in a relevant environment. When all technologies have reached this level of maturity, it is relatively easy to put together a cost and schedule for development that can be done, giving the project manager a green light to successful project execution.

TRL Evaluation:

Given the above categorization of critical technologies, a first cut was made at examining the space elevator elements in a work breakdown structure (WBS), and ranking them by TRL. The following Figures 2-4 list the space elevator WBS elements in the left column, and then rank them by color coding indicating the kind of development and testing likely required for maturity in the following columns. Colors indicated are as described above, red for the lowest TRL 1-2, (stop, we have a lot of work to do here); yellow for TRL 3-5 (send money and we will make it work); and green for TRL 6-9 (we know how to do this and can estimate a reasonable cost and schedule for development).

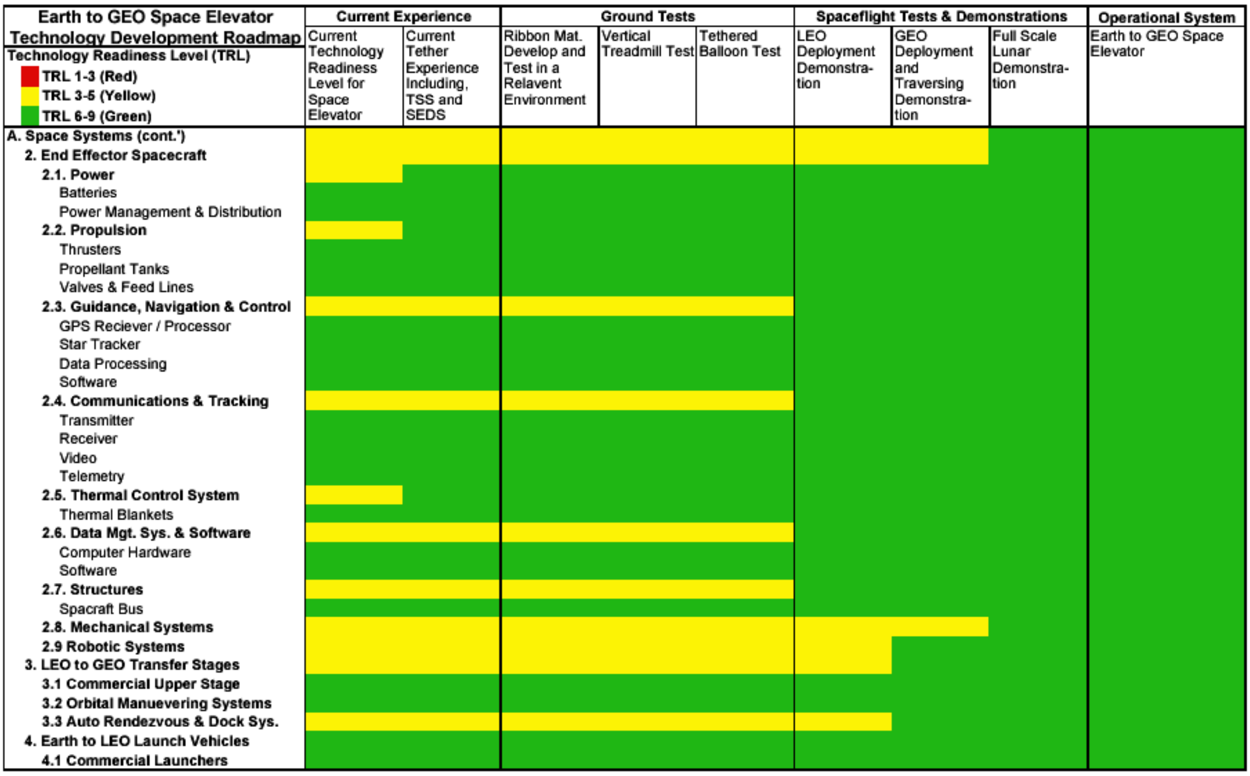
The columns following the WBS column are a progression of experiments and developments that will probably be needed to mature all the technologies and integrate them into a system that can be constructed. Beginning with the two "Current Experience" columns, the TRL rankings are nearly identical indicating where we think the technologies are today for all the space elevator systems. The next 3 columns under "Ground Tests" are designed to advance some technologies from a lower level TRL in red or yellow, to a higher TRL of yellow or green. Note that the chart extends color bands across all columns, but that not every experiment uses every technology. The next 3 columns under "Space Flight Tests and Demonstrations" are designed to advance mid-range technologies in yellow into integrated systems for flight in green. Once all, or nearly all the technologies have been advanced to an integrated systems level in green then space elevator construction would be ready to begin as indicated in the last column.



Earth to GEO Space Elevator Technology Development Roadmap	Current Experience		Ground Tests			Spaceflight Tests & Demonstrations			Operational System
Technology Readiness Level (TRL) 🟥 TRL 1-3 (Red) 🟨 TRL 3-5 (Yellow) 🟩 TRL 6-9 (Green)	Current Technology Readiness Level for Space Elevator	Current Tether Experience Including, TSS and SEDS	Ribbon Mat. Develop and Test in a Relavent Environment	Vertical Treadmill Test	Tethered Balloon Test	LEO Deployment Demonstra-tion	GEO Deployment and Traversing Demonstra-tion	Full Scale Lunar Demonstra-tion	Earth to GEO Space Elevator
A. Space Systems	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩
1. Ribbon Deployment Platform	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
1.1. Power	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
Solar Arrays	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
Batteries	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Power Management & Distribution	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
1.2. Propulsion	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
Thrusters	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Propellant Tanks	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Valves & Feed Lines	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
1.3. Guidance, Navigation & Control	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
GPS Reciever / Processor	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Star Tracker	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Control Moment Gyros	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Data Processing	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Software	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
1.4. Communications & Tracking	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
Transmitter	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Receiver	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Video	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Telemetry	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
1.5. Thermal Control System	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
Radiators	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
Thermal Blankets	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
1.6 Data Mgt. Sys. & Software	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩
Computer Hardware	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Software	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
1.7. Structures	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩
Spacraft Bus	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Ribbon Spool Support Structures	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
1.8. Mechanical Systems	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
Ribbon Spools	🟨 3	🟨 4	🟨	🟨	🟨	🟨	🟨	🟩	🟩
Solar Array Deployment Mechanism	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
Radiator Deployment Mechanism	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
1.9 Robotic Systems	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩
ISS Heritage Robotics	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩
Automatic Rendezvous & Docking	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩

Acronyms:
GPS – Global Positioning System
ISS – International Space Station
LEO – Low Earth Orbit
SEDS – Small Expendable-Tether Deployer System
TSS – Tethered Satellite System

Figure 2: WBS for the Ribbon Deployment Platform at GEO that will deploy the space elevator ribbon



Earth to GEO Space Elevator Technology Development Roadmap	**Current Experience**		**Ground Tests**			**Spaceflight Tests & Demonstrations**			**Operational System**
Technology Readiness Level (TRL) 🟥 **TRL 1-3 (Red)** 🟨 **TRL 3-5 (Yellow)** 🟩 **TRL 6-9 (Green)**	Current Technology Readiness Level for Space Elevator	Current Tether Experience Including, TSS and SEDS	Ribbon Mat. Develop and Test in a Relavent Environment	Vertical Treadmill Test	Tethered Balloon Test	LEO Deployment Demonstration	GEO Deployment and Traversing Demonstration	Full Scale Lunar Demonstration	Earth to GEO Space Elevator
A. Space Systems (cont.')	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩
2. End Effector Spacecraft	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩
2.1. Power	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Batteries	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Power Management & Distribution	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2.2. Propulsion	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Thrusters	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Propellant Tanks	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Valves & Feed Lines	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2.3. Guidance, Navigation & Control	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩
GPS Reciever / Processor	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Star Tracker	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Data Processing	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Software	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2.4. Communications & Tracking	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩
Transmitter	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Receiver	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Video	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Telemetry	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2.5. Thermal Control System	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Thermal Blankets	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2.6. Data Mgt. Sys. & Software	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩
Computer Hardware	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Software	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2.7. Structures	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩
Spacraft Bus	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2.8. Mechanical Systems	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩
2.9 Robotic Systems	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
3. LEO to GEO Transfer Stages	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
3.1 Commercial Upper Stage	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
3.2 Orbital Manuevering Systems	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
3.3 Auto Rendezvous & Dock Sys.	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
4. Earth to LEO Launch Vehicles	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
4.1 Commercial Launchers	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

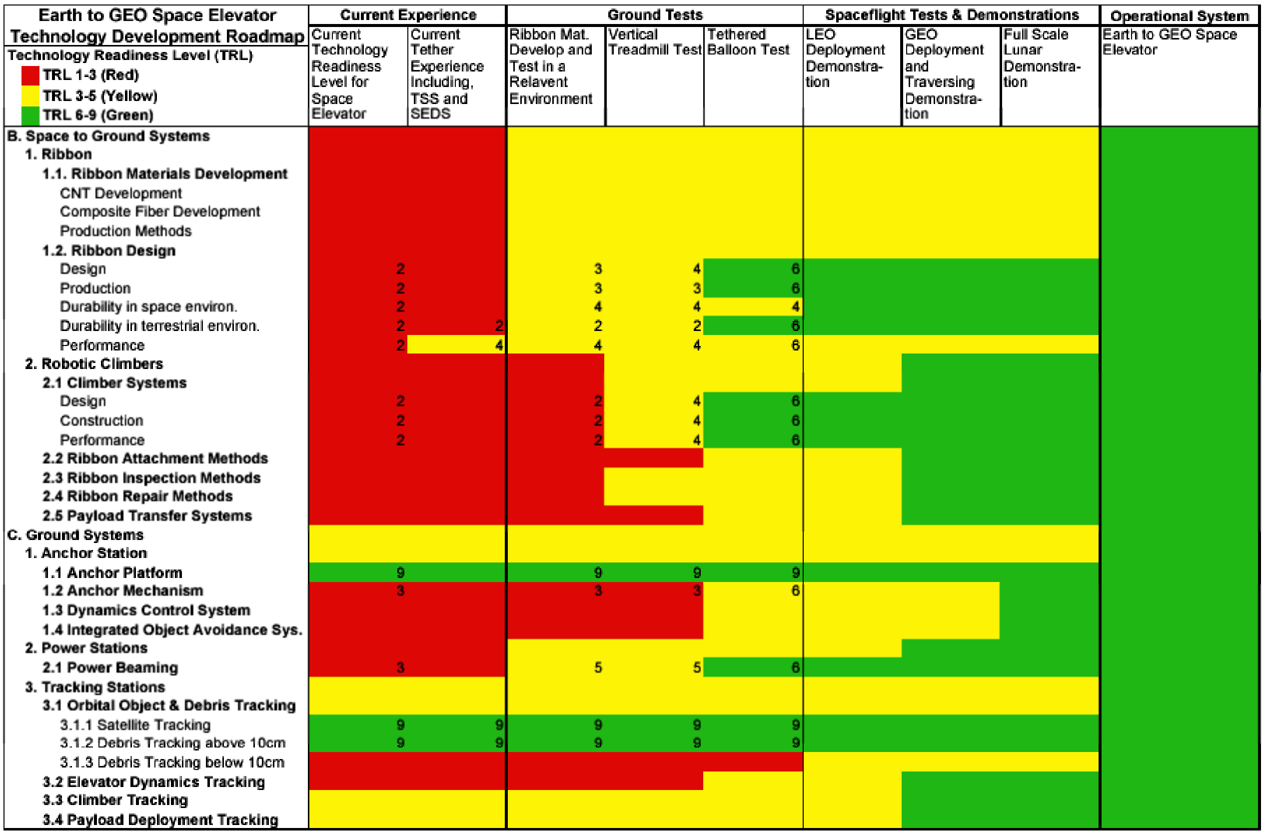
Figure 3: WBS for the End Effector Spacecraft that will control the lower end of the ribbon as it is deployed to Earth, the LEO to GEO Transfer Stages, and the Earth to LEO Launch Vehicles.

The numbering systems in the color-coded columns are more specific TRL indicators that have been identified so far. Future work includes more specific identification for each technology along with better plans for advancing the lower TRL technologies; and more specifics on testing approaches, flight experiments, and demonstration missions.

Low TRL Summary:

As can be seen in Figure 4, the lowest TRL technologies are in the Space to Ground Systems, and Ground Systems. In particular, Ribbon Materials Development, and Ribbon Design are at a TRL 2 indicating that an approach to their development has been formulated, but successful development has yet to occur. Ribbon materials and design are linked and will require extensive analysis and testing to ensure that the total system will meet the overall performance requirements of the elevator for mass and strength, assumed to be around 130 Giga-Pascals (GPa) for an earth-based space elevator. In addition, a full-length ribbon, whether continuous or spliced, is anticipated to be 60,000 to 100,000 km long, so mass production methods will be a consideration, too. Durability in the space environment, wear and tear of climbers, splicing methods, and repair methods are additional considerations for the ribbon materials and design to consider.

The climbers are also shown at a low TRL because of the automated tasks required of the climber for ribbon splicing, inspection, and repair—all at high speed on the order of 100 km per hour or more if possible. These are tasks that individually may not be difficult for machine operations on the ground, but incorporating these functions into a lightweight ribbon climber has never been done before.



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B. Space to Ground Systems	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟩
1. Ribbon	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟩
1.1. Ribbon Materials Development	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟩
CNT Development	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟩
Composite Fiber Development	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟩
Production Methods	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟩
1.2. Ribbon Design	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟩
Design	🟥 2	🟥	🟨 3	🟨 4	🟩 6	🟩	🟩	🟩	🟩
Production	🟥 2	🟥	🟨 3	🟨 3	🟩 6	🟩	🟩	🟩	🟩
Durability in space environ.	🟥 2	🟥	🟨 4	🟨 4	🟨 4	🟩	🟩	🟩	🟩
Durability in terrestrial environ.	🟥 2	🟥 2	🟨 2	🟨 2	🟩 6	🟩	🟩	🟩	🟩
Performance	🟥 2	🟨 4	🟨 4	🟨 4	🟨 6	🟨	🟨	🟨	🟩
2. Robotic Climbers	🟥	🟥	🟥	🟨	🟨	🟨	🟩	🟩	🟩
2.1 Climber Systems	🟥	🟥	🟥	🟨	🟨	🟨	🟩	🟩	🟩
Design	🟥 2	🟥	🟥 2	🟨 4	🟩 6	🟩	🟩	🟩	🟩
Construction	🟥 2	🟥	🟥 2	🟨 4	🟩 6	🟩	🟩	🟩	🟩
Performance	🟥 2	🟥	🟥 2	🟨 4	🟩 6	🟩	🟩	🟩	🟩
2.2 Ribbon Attachment Methods	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩
2.3 Ribbon Inspection Methods	🟥	🟥	🟥	🟨	🟨	🟨	🟩	🟩	🟩
2.4 Ribbon Repair Methods	🟥	🟥	🟥	🟨	🟨	🟨	🟩	🟩	🟩
2.5 Payload Transfer Systems	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩
C. Ground Systems	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩
1. Anchor Station	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩
1.1 Anchor Platform	🟩 9	🟩	🟩 9	🟩 9	🟩 9	🟩	🟩	🟩	🟩
1.2 Anchor Mechanism	🟥 3	🟥	🟥 3	🟥 3	🟨 6	🟨	🟨	🟩	🟩
1.3 Dynamics Control System	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟩	🟩
1.4 Integrated Object Avoidance Sys.	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟩	🟩
2. Power Stations	🟥	🟥	🟨	🟨	🟨	🟨	🟩	🟩	🟩
2.1 Power Beaming	🟥 3	🟥	🟨 5	🟨 5	🟩 6	🟩	🟩	🟩	🟩
3. Tracking Stations	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩
3.1 Orbital Object & Debris Tracking	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩
3.1.1 Satellite Tracking	🟩 9	🟩 9	🟩 9	🟩 9	🟩 9	🟩	🟩	🟩	🟩
3.1.2 Debris Tracking above 10cm	🟩 9	🟩 9	🟩 9	🟩 9	🟩 9	🟩	🟩	🟩	🟩
3.1.3 Debris Tracking below 10cm	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟩
3.2 Elevator Dynamics Tracking	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩
3.3 Climber Tracking	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
3.4 Payload Deployment Tracking	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩

Figure 4: WBS elements for the Space to Ground Systems including the ribbon and ribbon climbers, and all Ground Systems.

Several Ground Systems also have low TRL ratings. At the anchor station, mechanisms will be required to help control the overall dynamics of the system, perhaps moving the base and/or inducing waves in the ribbon for object avoidance. Such a system will need to be integrated with a more robust orbital object tracking system that is much more refined than the 10cm size-limit, multi-kilometer positioning range, and limited position prediction capabilities, of the systems in use today. Also, power beaming for the climbers has been demonstrated in the lab, but is at a low TRL because it has never been developed for large-scale systems that could beam surface generated power up to GEO altitudes.

CRITICAL PATH DEVELOPMENT

Numerous paths for technology development and demonstrations have been suggested utilizing ground experiments, air structures, LEO missions, the Space Shuttle, the *ISS*, GEO demonstration missions, demonstrations at the Earth-Lunar L1 or L2 points, and other locations. The following sections provide an overview of those ideas for consideration to help formulate a critical path for advancing the lower TRL technologies to a level ready for flight demonstration and eventual space elevator construction.

Technology Development:

Materials: Basic laboratory research & development is in progress on high-strength CNT composite fibers for a variety of uses including the earth-based space elevator. At this writing, fiber development still looks promising, but has yet to obtain a strength exceeding other commercially available carbon composites in common use today. Since the CNT fiber is only required for an earth-based space elevator, other high strength fibers could be used to develop the tethers and ribbons required for design and testing of the other parts of the system. Goals for ribbon performance have been set at about 130 GPa for the earth-based space elevator. Intermediate goals are needed for use of this same material in demonstration missions and other space elevator concepts. Specifically, intermediate CNT composite materials performance goals need to be identified for the 3 “Spaceflight Tests and Demonstration” missions indicated in Figures 2-4 above.

Ribbon Design: The design of the ribbon for assembly, durability and maintainability in the space environment is a critical technology for all space elevators including the demonstration missions. This has an integral relationship with the robotic climbers as well, since they will be doing the inspections, splicing, and repairs as needed to maintain the ribbon structure. Here, ground testing can advance the technology for ribbon design and repair in preparation for future space missions.

The first two ribbons to be designed could take separate approaches given its intended test requirements. In reference to Figure 4, the LEO Deployment Demonstration needs to survive the LEO environments, which will include atomic oxygen and space debris. For this test the use of CNT composites is important even if the high-strength requirements have yet to be obtained. The GEO Deployment and Traversing Demonstration could use conventional tether materials since its primary purpose is to develop control and robotic technologies.

Ground Tests: For both ribbons, extensive ground testing can prove the technology prior to flight. In particular, it has been suggested that a Vertical Treadmill Test could be developed that would simulate the ribbon undergoing the wear and tear of extensive traffic by the robotic crawlers. Incorporated into that test could be different crawlers designed to do high-speed ribbon inspections, splicing operations, and repairs.

At the same time, the Ribbon Materials Development and Testing in a Relevant Environment will expose them to simulated space environments to ensure their survivability to debris, radiation and atomic oxygen. These tests are linked to the repair tests above, in that any wear induced by the crawlers or the environment will need to be repaired or replaced without the loss of structural integrity of the entire system.

Once the robotic technology has matured and the ribbon design refined to permit maintenance then a Tether Balloon Test would be a logical next step for moving out of the laboratory and preparing for flight. The balloon test would consist of a high altitude tethered balloon equipped with a ribbon deployment system similar to a ribbon deployment spacecraft. Using a laser power beaming system for wireless power transmission, the deployment mechanism would demonstrate the deployment of a ribbon down to earth, and then demonstrate all robotic functions for the crawlers, including inspections, repairs, splicing, and payload transfers. Balloon tests would likely entail development and test of many of these functions independently and then culminating in a full up integrated test using prototype equipment that is near equivalent to the flight hardware.

Flight Experiments:

The baseline approach to flight experiments in developing space elevator technologies does not include use of our space-based laboratory, the *ISS*, or the Space Shuttle. But, if they were available, there are several ideas on how they could be utilized to help advance the long-term development of space elevator related technologies and systems. This includes fundamental research into the possible development in the microgravity environment of space, longer single wall carbon nano-tubes than can be created on earth due to the gravity environment, and fiber spinning experiments that might result in improvements to the ultimate strength of CNT composites. In addition, experiments in the microgravity environment on ribbon splicing, coatings and repairs would probably be useful in the development of the robotic climber systems.

Other ideas have included using the *ISS* as a platform for shorter tether tests in advance of, or as part of the LEO Deployment Demonstration previously mentioned. This could also be done by utilizing a modified Sparta platform as a free-flyer from the Shuttle or the *ISS* for ribbon deployment experiments. The recovery capability of these systems would make it possible to better examine the space environmental effects on the materials planned for the space elevator system and enable modification and reuse of the system for additional experiments.

Another interesting idea that would advance tether technology in general is the electrodynamics tether shown in Figure 5. This advanced concept provides re-boost of the *ISS* to maintain orbital altitude and could be used to lower the space station inclination over several years. The point of mentioning this here is that the *ISS* might have a useful life extension mission as part of a plan to develop space elevator technology beyond the timeframe it is currently programmed for science and exploration missions.

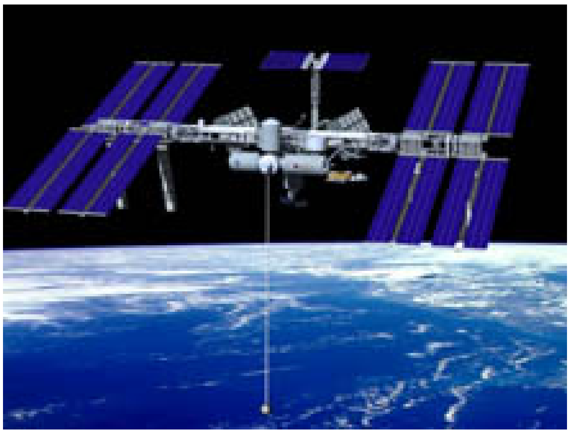

Figure 5: The *ISS*, with electrodynamics tether, could offer an approach to space elevator testing, too.

For the LEO section of the earth-based space elevator ribbon, it will eventually be important to have a major flight experiment like the LEO Deployment Demonstration to examine ribbon deployment, control, repair, and retraction methods, to insure that it can survive this environment and be repaired or replaced as needed. Such a mission is envisioned to be within the capabilities of a single medium class expendable launch vehicle (ELV) with the payload including a deployment spacecraft, ribbon spool, an end effecter spacecraft, and robotic climber for ribbon splicing, inspection, and repair. Additional investigations would include development of collision avoidance systems for this structure, along with more accurate tracking and trajectory projection systems for active and inactive objects in LEO.

An interesting concept that could someday utilize this technology is the LEO Space Elevator, or “Bridge to Space” concept envisioned by the Lockheed Martin Company (LMCO), Figure 6. This concept was proposed to capture payloads from a future suborbital space plane at 100 km altitude, and then lift the payload to the upper end of the elevator at 4000 km altitude, where when released it would enter a GEO transfer orbit. The LEO Deployment Demonstration would help test the feasibility of this concept.

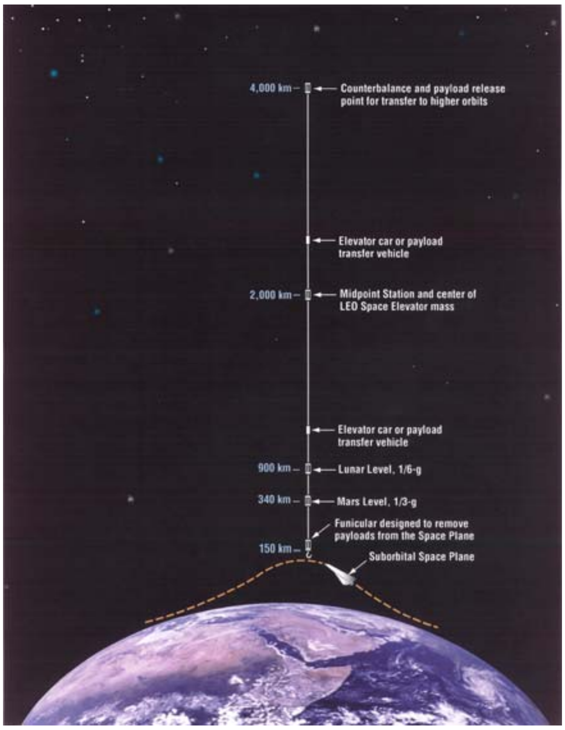

Figure 6: “Bridge to Space” concept for a LEO Space Elevator by LMCO.

Demonstration Missions:

Two major demonstration missions are envisioned as important for the earth-based space elevator: 1) the GEO Deployment and Traversing Demonstration, also known as the LEO to GEO Space Elevator; and 2) a Full scale Lunar Demonstration, also known as a Lunar Space Elevator or Lunar Towers. These demonstrations would prove the viability of space elevators for Earth, Mars, and the moons of other planetary systems. Even if the CNT composite material strengths are not obtainable in the near-term for an earth-based space elevator, the technology developed through these missions should provide significant infrastructure capabilities for access to many other planetary bodies, Figures 7 and 8.

The GEO Deployment and Traversing Demonstration is envisioned to be a major technology demonstration mission to prove that the space elevator ribbon dynamics can be controlled during deployment and during robotic traversing from end to end. This demonstration would utilize at least two heavy class ELV launches to GEO where the two spacecraft will rendezvous and deploy a 30,000 km ribbon; attach a robotic crawler vehicle to traverse the ribbon from end to end; test the spacecraft control systems given varying ribbon dynamics; and demonstrate the robotic crawlers capabilities for ribbon splicing, inspection and repair. In addition, these systems would be required to demonstrate power-beaming technologies for the robotic crawlers. Power could come from a variety of sources including ground stations, orbital platforms, or power platforms at GEO or at the counter balance end of the tether structure.

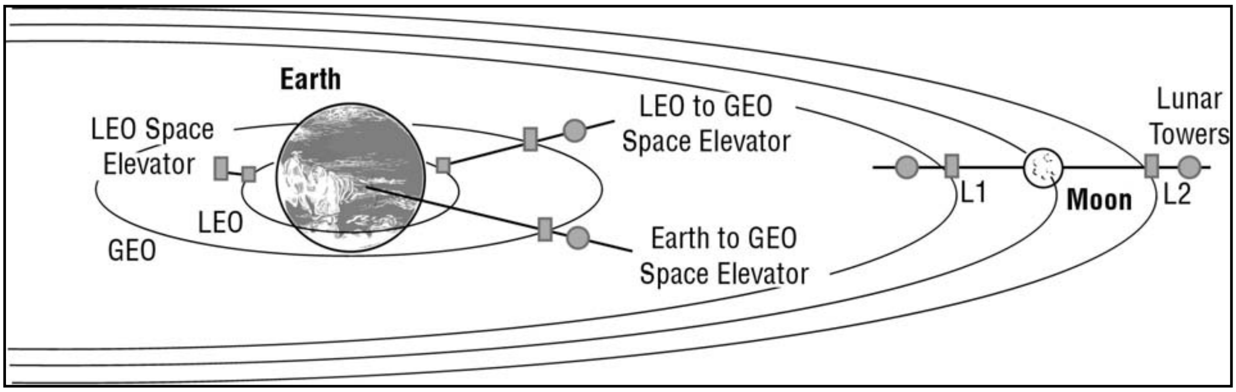

Figure 7: Concepts for space elevators around the Earth and Moon.

A similar technology has been proposed before for communications satellites where the transmitter is located at the lower end of a tether only a few thousand kilometers in altitude, and counter balanced by the power systems at the upper end of the tether. With the center of mass maintained at GEO, the systems operates like a LEO altitude satellite in a geostationary orbit for fast voice and data response to ground stations.

The Full Scale Lunar Demonstration is envisioned as a major technology demonstration mission for full deployment of a space elevator ribbon from the earth-moon L2 point in space on the far side of the moon. Four or more heavy class ELV launches to L2 will likely be needed to deploy multiple spacecraft for ribbon control at each end, ribbon deployment, robotic vehicles to traverse the ribbon from L2 to the surface of the moon, and an L2 docking station on the ribbon for payload transfers. This complex infrastructure has the potential to become part of a permanent lunar infrastructure providing access for ongoing missions to the surface of the moon. In addition, such a system would be a precursor to similar systems at the moons of Mars, and the moons around many outer planets.

The final step, referring back to Figures 2-4, is the development of an Operational System for an Earth to GEO Space Elevator. Once all the proceeding developments, tests, experiments and demonstrations have been successfully accomplished then construction should be feasible. These steps are far more extensive that proposed in the NIAC studies previously mentioned, but all have valid missions for advancing the technology. Somewhere in between this extensive set of testing and the simplified approach of the former study is probably the right answer. The intent here was to identify the full range of possible approaches for further analysis and debate.

Also, important to all these demonstration missions is their compatibility with future space infrastructures within the Earth-Moon system. Long-range plans should consider these potential developments so as not to inhibit their construction in the future. In particular, technology and policy plans need to be improved now that will deter the accumulation of debris in LEO and will begin taking steps toward removal of the debris already in orbit.

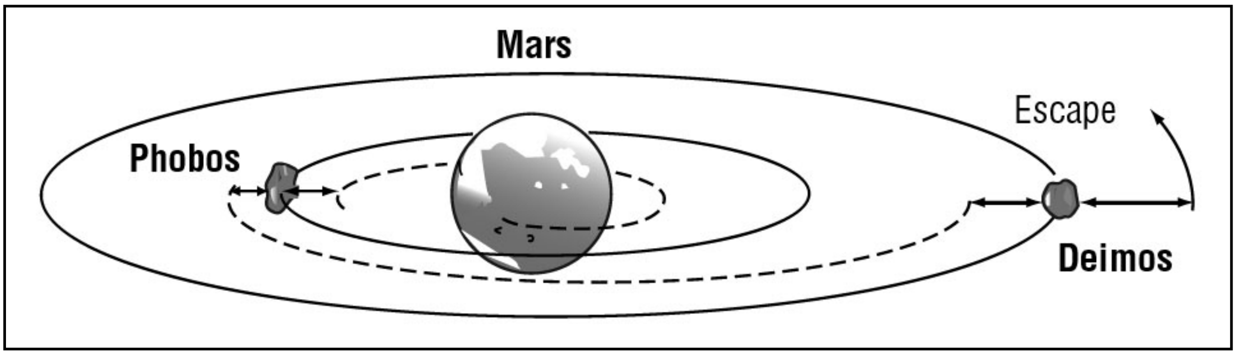

Figure 8: Concepts for space elevators at the moons of Mars to facilitate access to Mars and transportation between Mars and Earth.

CONCLUSIONS

Key Findings:
In conclusion, this paper finds that the most critical technologies for an Earth to GEO Space Elevator include CNT composite materials development and object avoidance technologies; that lack of successful development of these technologies need not preclude continued development of space elevator systems in general; and that the critical technologies required for the Earth to GEO Space Elevator are not required for similar systems at the Moon, Mars, Europa, or for other orbital tether systems at GEO, Luna, and other locations. CNT Composite development is the most critical technology development for the earth-based space elevator, without which the system may not be feasible.

Recommendations for Future Activities:
Space elevator developments in general should be investigated for Lunar L1 & L2 sites, Mars, and the Moons of outer planets. Many of these systems appear to be feasible with current technology and could become major permanent infrastructure elements for space science, human space exploration, and commercial space development. In addition, they could yield critical technology developments that would accelerate the feasibility of earth-based space elevator systems. Continued studies and technology developments on space elevators as outlined in this paper are highly recommended.

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