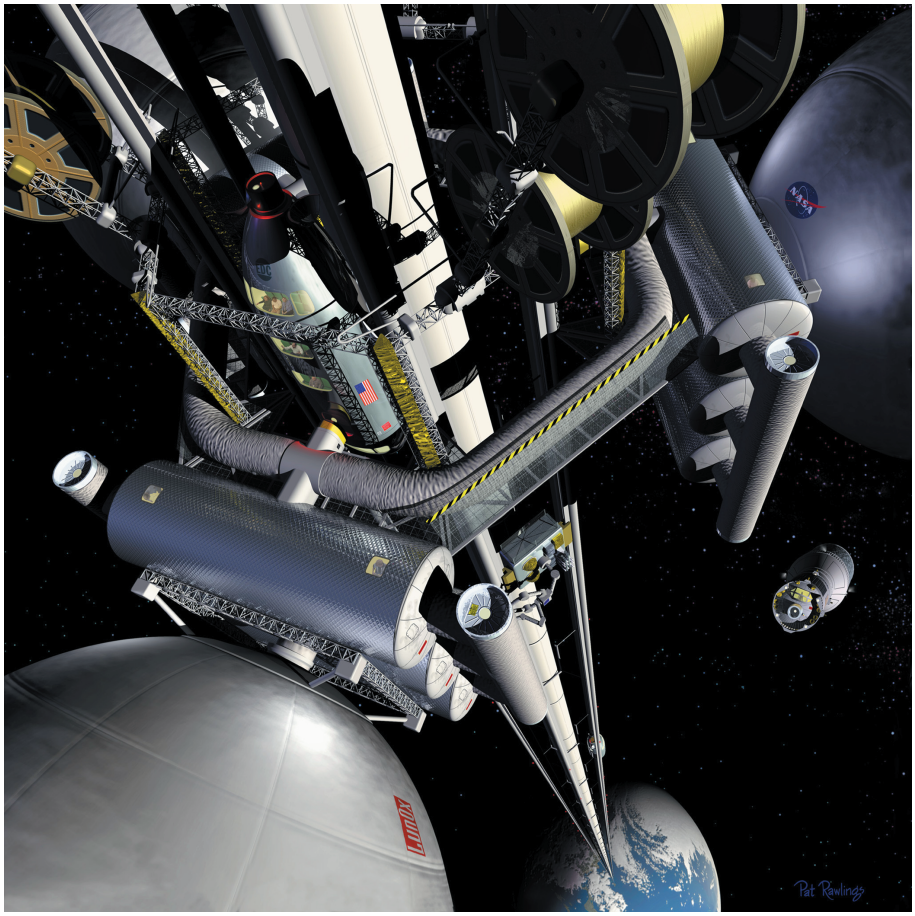
NASA/CP—2000–210429

Space Elevators

An Advanced Earth-Space Infrastructure for the New Millennium

Compiled by
D.V. Smitherman, Jr.
Marshall Space Flight Center, Huntsville, Alabama



This publication is based on the findings from the Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, NASA Marshall Space Flight Center, June 8–10, 1999.

August 2000

The NASA STI Program Office…in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results…even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at (301) 621–0134

- Telephone the NASA Access Help Desk at (301) 621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076–1320

NASA/CP—2000–210429

Space Elevators

An Advanced Earth-Space Infrastructure for the New Millennium

Compiled by
D.V. Smitherman, Jr.
Marshall Space Flight Center, Huntsville, Alabama

This publication is based on the findings from the Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, NASA Marshall Space Flight Center, June 8–10, 1999.

National Aeronautics and
Space Administration

Marshall Space Flight Center • Huntsville, Alabama 35812

August 2000

Acknowledgments

Sponsors: This publication is based on the findings from the Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, managed by David V. Smitherman, Jr., Architect, Technical Manager in the Advanced Projects Office, Flight Projects Directorate, NASA Marshall Space Flight Center, Huntsville, Alabama. The workshop was conducted June 8–10, 1999, by the Flight Projects Directorate in cooperation with the Advanced Projects Office, Office of Space Flight, NASA Headquarters, Washington, DC, and the Advanced Space Transportation Program, NASA Marshall Space Flight Center, Huntsville, Alabama.

Cover Artwork: NASA artwork of the space elevator was created by Pat Rawlings, Science Applications International Corporation. This illustration for a space elevator concept is taken from the geostationary transfer station looking down the length of the elevator structure toward Earth. Electromagnetic vehicles travel the length of the elevator to transfer passengers and cargo between Earth and space. Six vehicular tracks surround a high-strength tubular core structure fabricated from advanced carbon nanotube materials. Three tracks carry passengers and cargo vehicles, while the other three tracks provide for service vehicles that maintain the elevator systems. Large reels with high-strength cables work back and forth to provide small adjustments to the position of the geostation and an asteroid counterweight above (not shown) to maintain the center of mass for the entire structure at a geostationary point above the Earth. Inflatable spheres and space station modules provide habitable volumes for the transfer of passengers and cargo through the station to outbound orbital transfer vehicles.

Available from:

NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076–1320
(301) 621–0390

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
(703) 487–4650

TABLE OF CONTENTS

1. SUMMARY 1

1.1 Introduction: What is a Space Elevator? 1
1.2 Key Findings From the Workshop 1
1.3 Future Directions 2
1.4 Technology Demonstrations 2

2. SPACE ELEVATOR CONCEPTS 2

2.1 Brief History 2
2.2 A Space Elevator Concept 3
2.3 Space Elevator Basics 4

3. TECHNOLOGY DEVELOPMENT PATHS 6

3.1 Materials 6
3.2 Tension Structures 7
3.3 Compression Structures 12
3.4 Electromagnetic Propulsion 14
3.5 Supporting Infrastructure 18

4. ISSUES 23

4.1 Environmental Issues 23
4.2 Safety Issues 25

5. CONCLUSIONS AND RECOMMENDATIONS 29

5.1 Pros for Building Space Elevators 29
5.2 Cons Against Building Space Elevators 30
5.3 Concerns and Possible Solutions 31
5.4 Recommendations 31

APPENDIX A—WORKSHOP PARTICIPANTS AND CONTRIBUTORS 33

A.1 Workshop Participants 33
A.2 Additional Contributors and Virtual Research Center Participants 33

REFERENCES 34

BIBLIOGRAPHY 36

LIST OF FIGURES

1. Technology demonstration roadmap. Critical technologies that need to be demonstrated prior to space elevator development include tether systems in space, tall towers on Earth, and electromagnetic propulsion systems. Developing the technologies and integrating these systems together could lead toward Earth to GEO space elevator developments in the latter part of the 21st century. 3

2. A space elevator concept 5

3. Yielding of high-strength steel as compared to carbon nanotube rope (SWNT). Note that the strength required for space elevator construction is thought to be ≈62.5 GPa, but the actual strength of a carbon nanotube rope may be much higher than that. 6

4. LEO space elevator concept 8

5. LEO space elevator for lunar transfers 9

6. Momentum exchange facility. This orbital transfer station uses a rotating momentum exchange tether system to transfer payloads to higher orbits. An electrodynamic tether propulsion vehicle is shown over the horizon. 11

7. Earth orbiting and lunar space elevator concepts 11

8. Mars space elevator transportation system 11

9. Tall tower concept 13

10. High-altitude multipurpose tower concept 13

11. Launch arch concept 14

12. Concept for a high-speed electromagnetic propulsion vehicle for the space elevator 15

13. A MagLev concept called Transit used for both trains and van-sized vehicles 16

14. MagLifter launch assist concept 17

15. Electromagnetic launch systems 17

16 Reusable space transfer vehicle and propellant servicing platform 19

17. Electromagnetic gun launch system for delivery of raw materials to orbit 19

LIST OF FIGURES (Continued)

18. Space business park. A multiuse space station facility for compatible businesses including tourism, sports, film production, and entertainment, as well as support to satellite services, research and development facilities, and on-orbit processing and manufacturing. 19

19. Space solar-powered satellite 20

20. Modular robotic systems for space assembly, maintenance, and repair 20

21. Asteroid attached to the space elevator beyond GEO to counterbalance the system 21

22. Asteroid materials mining 21

23. "Blue Moon tours" is a concept for what space transportation out to the Moon and back could be like as part of a future space development infrastructure 22

24. Concept for an ocean platform city for the base of a space elevator 23

25. Tracked space satellites and debris distribution 25

26. Sizing tether strands based on repairs per day 26

27. Orbital periods 27

28. Maneuvers required by a space station (using *ISS* as an example) to avoid a fixed space elevator structure in LEO 27

29. Bending the space elevator for collision avoidance 28

30. Space elevator cross section. Conceptual cross section of a space elevator showing high-speed passenger modules, cargo carrier, maintenance and repair robot, and a lateral propulsion module for collision avoidance control at any point on the elevator structure. Note also that the cross section of the entire structure is large enough that a direct hit from a large upper stage would not break all of the structural cables. This kind of basic design thinking will need to be put into the space elevator to ensure that catastrophic failure does not occur. 28

LIST OF ACRONYMS

AO	atomic oxygen
g	gravity
GEO	geostationary Earth orbit
GPa	Giga Pascal
GPS	Global Positioning System
HRV	highly reusable vehicle
ISS	*International Space Station*
LEO	low-Earth orbit
MagLev	magnetic levitation
MagLifter	magnetic lifter
MEO	middle-Earth orbit
NASA	National Aeronautics and Space Administration
ProSEDS	Propulsive Small Expendable Deployer System
SEDS	Small Expendable Deployer System
SSTO	single-stage-to-orbit
SWNT	single-wall nanotubes
TSS	Tethered Satellite System
UV	ultraviolet

CONFERENCE PUBLICATION

SPACE ELEVATORS
AN ADVANCED EARTH-SPACE INFRASTRUCTURE FOR THE NEW MILLENNIUM

1. SUMMARY

This conference publication, "Space Elevators: An Advanced Earth-Space Infrastructure for the New Millennium," is based on findings from the Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, held in June 1999 at the NASA Marshall Space Flight Center, Huntsville, Alabama. Subsequent consultation and review of the document with the participants was made prior to publication to clarify technical data and ensure overall consensus on the content of this publication.

1.1 Introduction: What is a Space Elevator?

A space elevator is a physical connection from the surface of the Earth to a geostationary Earth orbit (GEO) above the Earth ≈35,786 km in altitude. Its center of mass is at the geostationary point such that it has a 24-hr orbit and stays over the same point above the equator as the Earth rotates on its axis. The vision is that a space elevator would be utilized as a transportation and utility system for moving people, payloads, power, and gases between the surface of the Earth and space. It makes the physical connection from Earth to space in the same way a bridge connects two cities across a body of water (see cover art and fig. 2).

The Earth to GEO space elevator is not feasible today, but could be an important concept for the future development of space in the latter part of the 21st century. It has the potential to provide mass transportation to space in the same way highways, railroads, power lines, and pipelines provide mass transportation across the Earth's surface. The low energy requirements for moving payloads up and down the elevator could make it possible to achieve cost to orbit <$10/kg. The potential for low-cost mass transportation to space makes consideration of the technology paths required for space elevator construction very important today. The technology paths are beneficial to many other developments and can yield incremental benefits as progress is made toward making space elevator construction feasible.

1.2 Key Findings From the Workshop

A number of issues were raised and resolved during the workshop that has helped to bring the space elevator concept out of the realm of science fiction and into the realm of possibility. These key findings included the following:

1. Materials technology needed for space elevator construction is in the development process in laboratories today. Continued research will likely produce the high-strength carbon nanotube materials needed for efficient space elevator construction and for a wide variety of new and improved products.

2. The tallest structure today is 629 m in height. Buildings and towers can be constructed many kilometers in height today using conventional construction materials and methods. These heights have not been attempted because there has not been a demonstrated need. Advanced materials and new construction methods could make it possible to construct towers tens, hundreds, and perhaps thousands of kilometers in height.

3. A tether structure hanging down from GEO connected to a tall tower constructed up from the Earth appears to be the most efficient and technically feasible method for space elevator construction.

4. Climatic conditions at the equatorial zone are very mild in comparison to more northern and southern latitudes, making construction along the equator ideal from a weather hazard standpoint. It is not physically possible for hurricanes and tornados to form at the equator.

5. The space elevator structure is inherently flexible over its great length and can be designed to avoid major hazards. Minor hits from asteroid debris are inevitable and will require standard repair procedures. A simple analogy is to think of the space elevator structure as a 36,000-km-long highway that will require ongoing maintenance and repair.

The space elevator concept is incredibly large and complex, but no issues were found to be without some obvious course for resolution. Given proper planning for the development of critical technologies, it appears that space elevator construction could become feasible.

1.3 Future Directions

Five primary technology thrusts were identified as critical to the development of space elevators in the 21st century. All have many other near-term applications for new products and services on Earth and in space. They are as follows:

1. Develop advanced high-strength materials like the graphite, alumina, and quartz whiskers that exhibit laboratory strengths >20 GPa. Continue development of the carbon nanotube materials that exhibit strengths 100 times stronger than steel. Introduce these new lightweight, high-strength materials to the commercial, space, and military markets for new and improved product developments (see 3.1 Materials).

2. Continue development of space tether technologies for space transportation systems to gain experience in the deployment and control of long structures. Utilize higher strength materials as they become available. Continue analysis and plan for demonstration of momentum exchange and low-Earth orbit (LEO) space elevator facilities for low-cost, in-space transfer to GEO (see 3.2 Tension Structures).

3. Introduce lightweight composite structural materials to the general construction industry for the development of tall tower and building construction systems. Foster the development of multikilometer-height towers for commercial applications; i.e., communications, science observatories, and launch platforms (see 3.3 Compression Structures).

4. Develop high-speed electromagnetic propulsion for mass transportation systems, launch assist systems, and high-velocity launch rails. Integrate electromagnetic propulsion devices into conventional construction industry systems; i.e., doors, elevators, conveyors, etc. (see 3.4 Electromagnetic Propulsion).

5. Develop transportation, utility, and facility infrastructures to support space construction and industrial development. Key components include highly reusable space launch systems, reusable in-space transportation, and space facility support from LEO to GEO (see 3.5 Supporting Infrastructures).

Advances in these five areas over the next 10 to 20 years will lay the foundation for future space elevator developments. Other benefits to space transportation, Earth-based infrastructures, products, and services are evident and are discussed in the details of this publication.

1.4 Technology Demonstrations

Technology demonstrations were identified for tethers, towers, and electromagnetic systems as being critical to a technology progression toward space elevator construction capabilities during the 21st century. Figure 1 illustrates one logical course of events over an indefinite period of time leading up to the full-scale development of Earth to GEO space elevators.

More details on many of these technology demonstrations as well as other related potential developments and benefits are discussed in this publication. The intent is to show that these technology demonstrations and developments can provide incremental benefits and are logical to pursue for their own merit in addition to their obvious relationship to future space elevator developments.

2. SPACE ELEVATOR CONCEPTS

The following sections provide an overview of the basic Earth to GEO space elevator concept as well as a number of other related space elevator concepts that have been envisioned over the years. This basic concept for building a structure from the surface of the Earth into space has been around for a long time, but was not well known or even seriously considered from an engineering standpoint until the latter part of the 20th century.

2.1 Brief History

The idea of building a tower from the surface of the Earth into space, the sky, or the heavens dates back to some of the very earliest known manuscripts in existence. The writings of Moses, about 1450 BC, in his book *Genesis*, chapter 11, reference an earlier civilization that in about 2100 BC tried to build a tower to heaven out of brick and tar. This structure is commonly called the Tower of Babel, and was reported to be located in Babylon, a city in ancient Mesopotamia. Later in chapter 28, about 1900 BC, Jacob had a dream about a staircase or ladder built to heaven, commonly called Jacob's Ladder. More contemporary writings on the subject date back to K.E. Tsiolkovski in his manuscript "Speculations about Earth and Sky and on Vesta," published in 1895. No doubt the idea for building a tower from the surface of the Earth into space has been dreamed, invented, and reinvented many times throughout modern civilization.

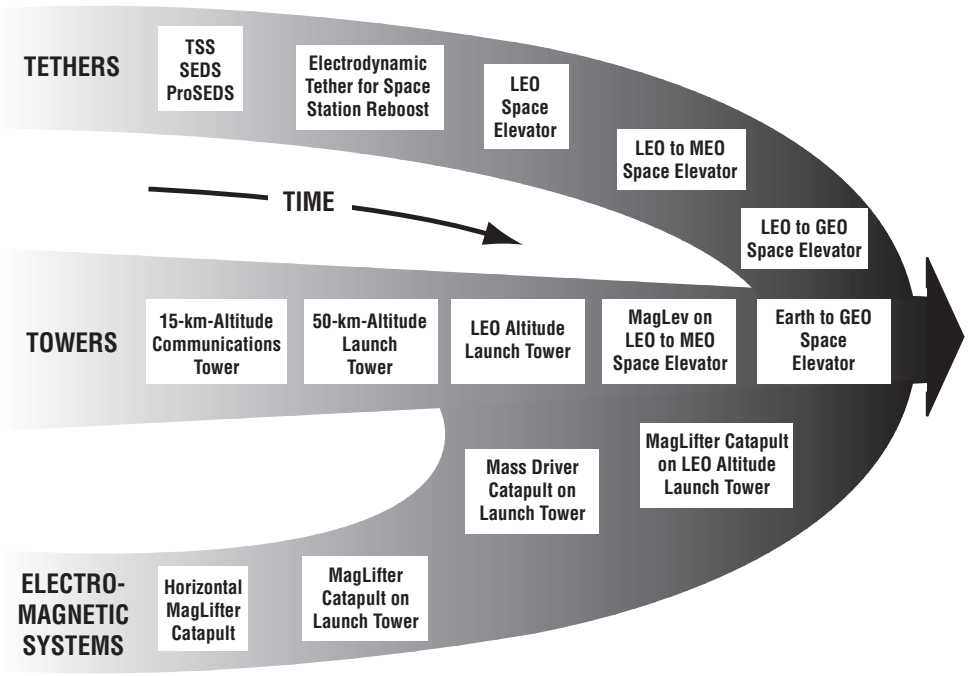


Figure 1. Technology demonstration roadmap.[1] Critical technologies that need to be demonstrated prior to space elevator development include tether systems in space, tall towers on Earth, and electromagnetic propulsion systems. Developing the technologies and integrating these systems together could lead toward Earth to GEO space elevator developments in the latter part of the 21st century.

The first published account describing a space elevator that recognized the utility of geosynchronous orbit did not occur until 1960. Yuri Artsutanov, a Leningrad engineer, published a nontechnical story in a Sunday supplement to *Pravda*, which did not become known in the West. Later, in 1966, a group of American Oceanographers led by John Isaacs published a short article in *Science* on a pair of whisker-thin wires hanging from a geostationary satellite. Again, this did not come to the attention of the space flight engineering community. Finally in 1975, Jerome Pearson, working at the Air Force Research Laboratory, also independently invented the space elevator and published a technical paper in *Acta Astronautica*. This publication brought the concept to the attention of the space flight community and later inspired Sir Arthur Clarke to write his novel, *The Fountains of Paradise*, about a space elevator based on a fictionalized Sri Lanka, which brought the concept to the attention of the entire world. Pearson later participated in the NASA Marshall tether workshops beginning in 1983, and brought the space elevator concept into the space tether technical community. The bibliography in this publication contains many contemporary writings on this and related subjects since 1960.

Today, the world's tallest structure is a stayed television transmitting tower near Fargo, North Dakota, USA. It was built in 1963 for KTHI-TV, and stands 629 m high. The CN Tower in Toronto, Ontario, Canada is the world's tallest building. It was built from 1973–1975, is 553 m in height, and has the world's highest observation deck at 447 m. The world's tallest office building is the Petronas Towers in Kuala Lumpur, Malaysia.[2] The twin towers stand 452 m in height, ≈10 m taller than the Sears Tower in Chicago, Illinois, USA. The height of existing towers and buildings today are not limited by construction technology or by materials strength. Even as far back as the 1930's, architects such as Frank Lloyd Wright were making designs for mile-tall skyscrapers. Conventional materials and methods make it possible even today to construct towers many kilometers in height. There simply has not been a compelling need to build structures any taller. In the following sections the space elevator and related concepts will be examined in some detail to show its potential feasibility, and some approaches for developing the technology required for its construction.

2.2 A Space Elevator Concept

A baseline concept for a space elevator was created during the workshop to illustrate its purpose, scale, and complexity. As described in the introduction, a space elevator is a physical connection from the surface of the Earth to GEO above the Earth. It has a 24-hr orbit above the equator in sync with the Earth's rotation. The intended use is for transportation of

payloads (including people), power, and gases between the surface of the Earth and space. It is literally a mass transportation system equivalent to a highway, railway, pipeline, and power line that connects our planet to the space frontier.

Beginning at the base, as illustrated in figure 2(a), this space elevator is envisioned to emerge from a platform at sea. The platform works like a seaport where cargo and passengers make their transfers from terrestrial transportation systems to the space elevator vehicles. It would likely include all the facilities of a small tourist town, including a marina, airport, hotels, restaurants, shops, and medical facilities. In the foreground a space elevator vehicle can be seen on the electromagnetic track that runs from the loading platform up the elevator structure into the sky.

A sea platform was selected because it illustrates a remote location in international waters. The remote location is desirable from a safety standpoint, at least for the first attempt when the risk of failure is the highest. Also, its location in international waters would be appropriate for a project of this scope that will probably require international cooperation and consensus to succeed. There was some discussion over whether the base would be fixed to the ocean floor or could actually float and move if needed. Either approach may be feasible, as well as land sites along the equator in South America, Africa, or equatorial island nations.

Moving up the elevator, figure 2(b) illustrates a concept for high-altitude support and control of the elevator tower through the use of inflatable platforms. This concept may be useful during early construction phases; however, it was determined that tall tower construction through the atmosphere is possible today using near conventional construction materials and methods.

From the top of the tower to the station at GEO is a long 36,000-km ride. Figure 2(c) illustrates a concept for an electromagnetic-propelled vehicle that can travel thousands of kilometers per hour, suspended in a track, with no moving parts (wheels) in contact with the elevator rails. This type of propulsion system was considered important to the success of a space elevator system, since any other type of mechanical system would require traction wheels that would be much slower and cause considerable wear on the vehicle and elevator structure. Acceleration and braking are envisioned by electromagnetic means such that energy is used to accelerate the vehicle to great speeds, and energy is recovered through the braking process, requiring advanced energy management systems that will make the total system very energy efficient. The vehicle is completely reusable, and returns to the base port on Earth, transferring passengers and cargo back down.

At the GEO transfer station (fig. 2(d)), passengers and cargo are transferred into the station or to outbound space transfer vehicles. This station is the center of gravity for the total system; consequently, large reels are illustrated to adjust the location of the station, tension of the structure, and the counterbalance mass. Docking ports provide access to space transfer vehicles at GEO, and an inflatable habitation structure is shown for living and working environments, perhaps rotating to provide some artificial gravity.

Beyond the GEO transfer station, other outbound vehicles can continue on the elevator track through the asteroid counterbalance (fig. 2(e)) to the end of the structure at 47,000 km where the end is traveling at near escape velocity. Minimal energy is required for launch to the Moon or other deep space destinations because the rotation of the elevator in its 24-hr orbit with the Earth acts like a sling beyond GEO to throw its payloads out of orbit. Without the counterbalance mass, the space elevator structure would be ≈144,000 km in length.

2.3 Space Elevator Basics

The most complex and demanding concept for a space elevator is the Earth to GEO space elevator, the primary topic of this publication. In this system, illustrated in figure 2, the elevator center-of-mass station is at GEO; the tether structure "hangs" down over 35,000 km to the Earth with no relative horizontal velocity and connects to a tall tower constructed from an ocean-based platform. The structure is designed integrally with six tracks for electromagnetic vehicles to travel continuously up and down the elevator structure. If a payload is released in LEO, it would need a propulsion system to increase its orbital velocity from that of GEO (3.1 km/sec) to that of LEO (7.7 km/sec).[3] Payloads released above GEO would be released into a transfer ellipse to a higher altitude. Release along the upper section of the tether at an altitude of 47,000 km would provide for Earth escape.[4] At the base, the tether structure in tension connects to a tall tower in compression. The taller the tower the better, since it is the lower section, as the structure approaches the Earth, that has the greatest impact on the systems' structural strength requirements and diameter at GEO.

One of the most common misconceptions about the space elevator concept is the assertion that materials strong enough to span the 36,000-km height from the surface of the Earth to GEO are unavailable. But, it is theoretically possible to build a structure of this size out of any common structural material by simply increasing its thickness to compensate for the high tensile or compressive loads. The problem is that for most readily available construction materials, it simply is not practical, due to the massive quantity and associated cost that would be involved. So finding the right material in combination with the right construction method is the key to success.

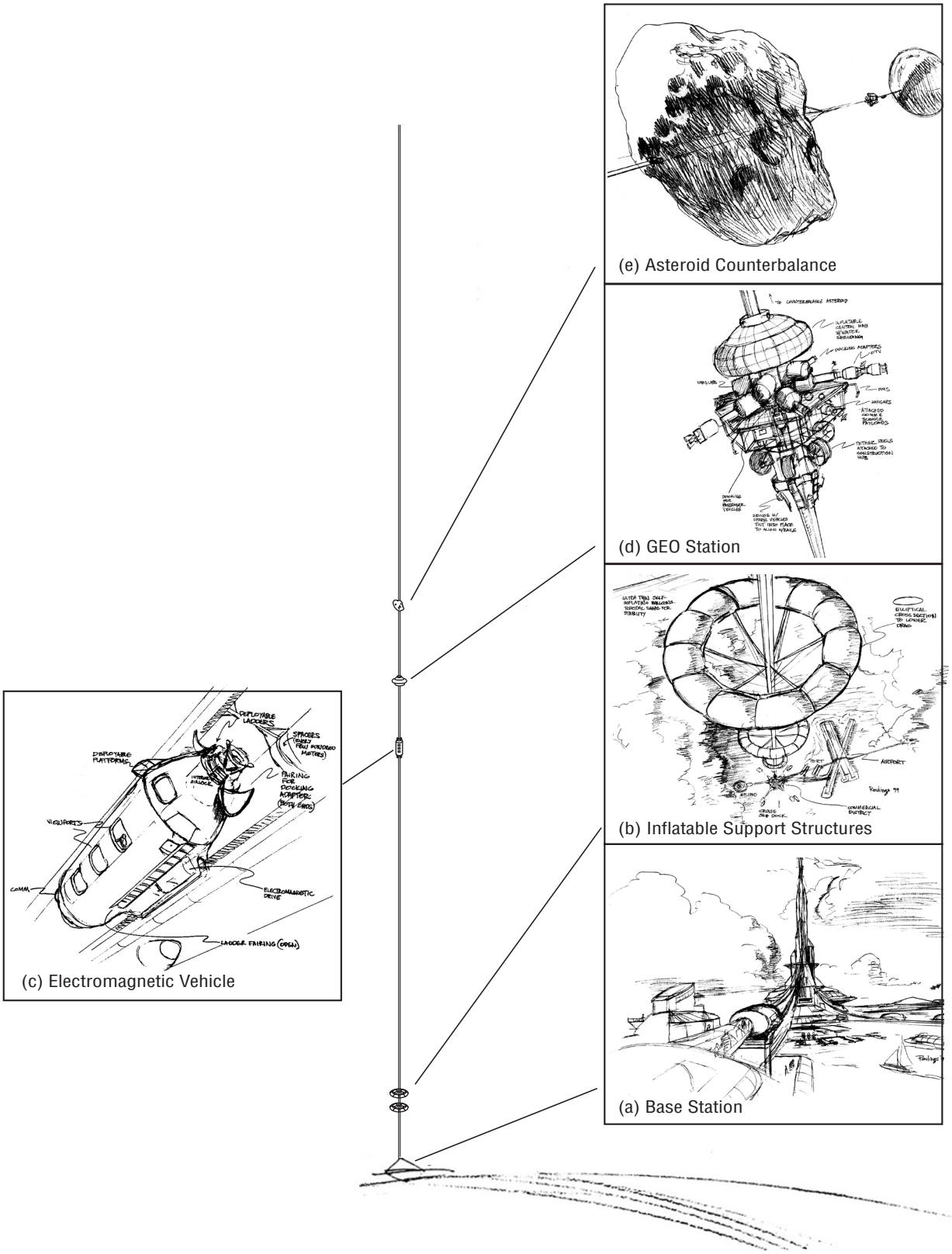


Figure 2. A space elevator concept.[5]

Comparisons have been made between the mass of materials required for a tension structure versus a compression structure from Earth to GEO. Interestingly, it was found that when using materials of the same strength-to-density ratio, the compression structure was actually less massive. The problem with compression structures or tall towers is that failure is usually through buckling, and most materials are actually stronger in tension than in compression. So, the ideal structure will likely be a combination of a tall tower in compression connected to a tension structure. For example, a tower 3,000 km in height built with PBO fibers (a high-strength polyaramid fiber available today with a strength of 5.8 GPa), connected to a tether extending the rest of the way to GEO could be 150 times less massive than a tensile structure alone. This tall tower/tether concept uses pressurization of the tower structural members, like a balloon, to convert the tower section from a compression structure to a tension structure.[6] Many early engineering concepts for the Earth to GEO space elevator have assumed a requirement for a diamond-filament cable. Diamond was used because it exhibited the strongest tensile and compressive material strengths available at that time. Now, new materials in the laboratory also hold promise and will be discussed in later sections.

It was determined that the energy required to move a payload along the length of a space elevator from the ground to geostationary orbit could be very low—approximately 14.8 kWh/kg. At today's energy cost of $0.10/kWh, the cost would be $1.48/kg.[7] In other words, a 12,000-kg Shuttle payload would have a low energy cost ($17,760) for a trip to GEO and a passenger with baggage at 150 kg would have an energy cost of $222. Of course the price would be higher, but it is well known that all mass transportation systems in operation today operate at a total cost that is only a fraction above the actual energy cost. It is the high usage of the system that makes them economically feasible. This is the potential that makes the space elevator so attractive.

3. TECHNOLOGY DEVELOPMENT PATHS

Five primary technology paths, or thrusts, were identified as critical for the development of space elevators: materials, tension structures, compression structures, electromagnetic propulsion, and supporting infrastructures. As stated in the summary, advances in these five areas over the next 10 to 20 years will lay the foundation for future space elevator developments in the latter part of the 21st century.

3.1 Materials

The lightest and strongest materials readily available today are the graphite epoxy composite materials that are commonly used in aerospace applications; but, the material strengths required for space elevator development appear to be far more demanding. Further development of advanced, lightweight, high-strength materials will be important; in particular, the continued development of a new material known as carbon nanotubes that has exhibited laboratory strengths 100 times stronger than steel with only a fraction of the weight. Figure 3 shows a comparison between high-strength steel and carbon nanotubes.

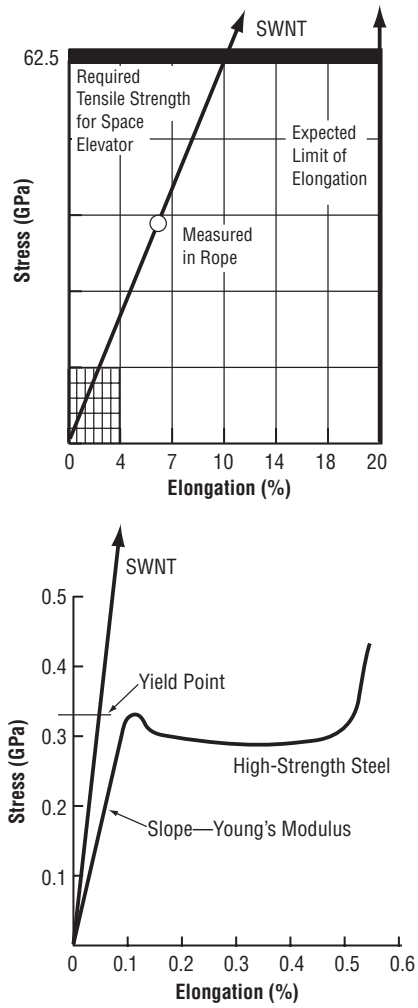


Figure 3. Yielding of high-strength steel as compared to carbon nanotube rope (SWNT).[8] Note that the strength required for space elevator construction is thought to be ≈62.5 GPa, but the actual strength of a carbon nanotube rope may be much higher than that.

To demonstrate the difference between current technology and the potential carbon nanotubes offer, a comparison of the two are made. If the space elevator was assumed to be a tapered, solid uniform structure using the strongest composite materials available today (Spectra or PBO graphite epoxy), the diameter at GEO would be 2 km and would taper down to 1 mm at the Earth's surface. The mass of the tethered structure would total approximately 60×10^{12} tons. If carbon nanotubes can be made into continuous structural members, then the diameter at GEO would potentially be as small as 0.26 mm, 0.15 mm at the Earth's surface; and the total tether mass would be only 9.2 tons.[7] This is the type of material that is needed because it would then be possible to increase the thickness of the carbon nanotube structure as needed to carry the electromagnetic systems required for space elevator operations.

At present, production of carbon nanotubes is very expensive and limited in quantity. Current laboratory production is accomplished by using a laser to vaporize a plug of graphite and then condensing the resulting matter to grow the nanotubes. This process coverts 90 percent of carbon to nanotube materials. However, the longest nanotubes produced to date are no more than a few microns in length.[8]

Carbon nanotubes are the first high-tensile strength, electrically and thermally conductive molecules. There are numerous commercial applications for carbon nanotube materials in existing markets, and potentially many new applications that cannot be envisioned today. Introduction into these markets could yield a demand for thousands of tons per year. Ideas generated in the workshop for carbon nanotube applications included the following:

- Structural applications for all types of existing aircraft, ships, automobiles, trains, etc.
- Future integrated structures and engine components for hypersonic flight vehicles
- Pressure vessels for flight vehicles
- Supersonic parachutes for commercial aircraft and reentry vehicles
- Lightweight armor for vehicles and personnel
- Structural members for buildings and towers many kilometers in height
- Earthquake-resistant structures
- Electronic circuit devices with densities four orders of magnitude greater than present
- Power transmission lines and towers
- Super flywheel energy storage devices
- Antennas at optical wavelengths
- Electrodes for high-energy density batteries
- Integration of structures with thermal management systems for flight vehicles
- Fabrics for better spacesuits and other thermal protection applications.

Although the carbon nanotube is shown here to have the potential to be the ideal material for space elevator construction, there are other alternatives; some will be discussed in the following sections. The important point is that lightweight, high-strength materials that are many times better than currently available are theoretically possible and should be pursued for the space elevator concept as well as for the many other applications that could benefit along the way.

3.2 Tension Structures

The second technology area is in the continued development of tension structures for space applications. This includes LEO space elevator facilities and momentum exchange facilities for permanent reusable in-space transportation from LEO to GEO altitudes and beyond. Similar applications for space transfer systems at the Moon and Mars could be pursued to develop permanent space transportation infrastructure for ongoing exploration and development at those locations. It is envisioned that these new systems would utilize higher strength materials as they become available and would build on the experience gained in the deployment and control of longer and longer structures.

Several concepts for the development of space elevators are examined in this section to provide an overview of what is possible in the near term and to begin examining in more detail the complexities of the Earth-based space elevator for the far term. This includes an overview of LEO space elevators, momentum exchange concepts, a lunar space elevator concept, and then concepts for space elevators in the Mars system.

3.2.1 Low-Earth Orbit Space Elevator Concepts

The LEO space elevator is an intermediate version of the Earth surface to GEO space elevator concept, and appears to be feasible today using existing high-strength materials and space technology (fig. 4). It works by placing the system's midpoint station, and center of gravity, in a relatively low-Earth orbit and extending one cable down so that it points

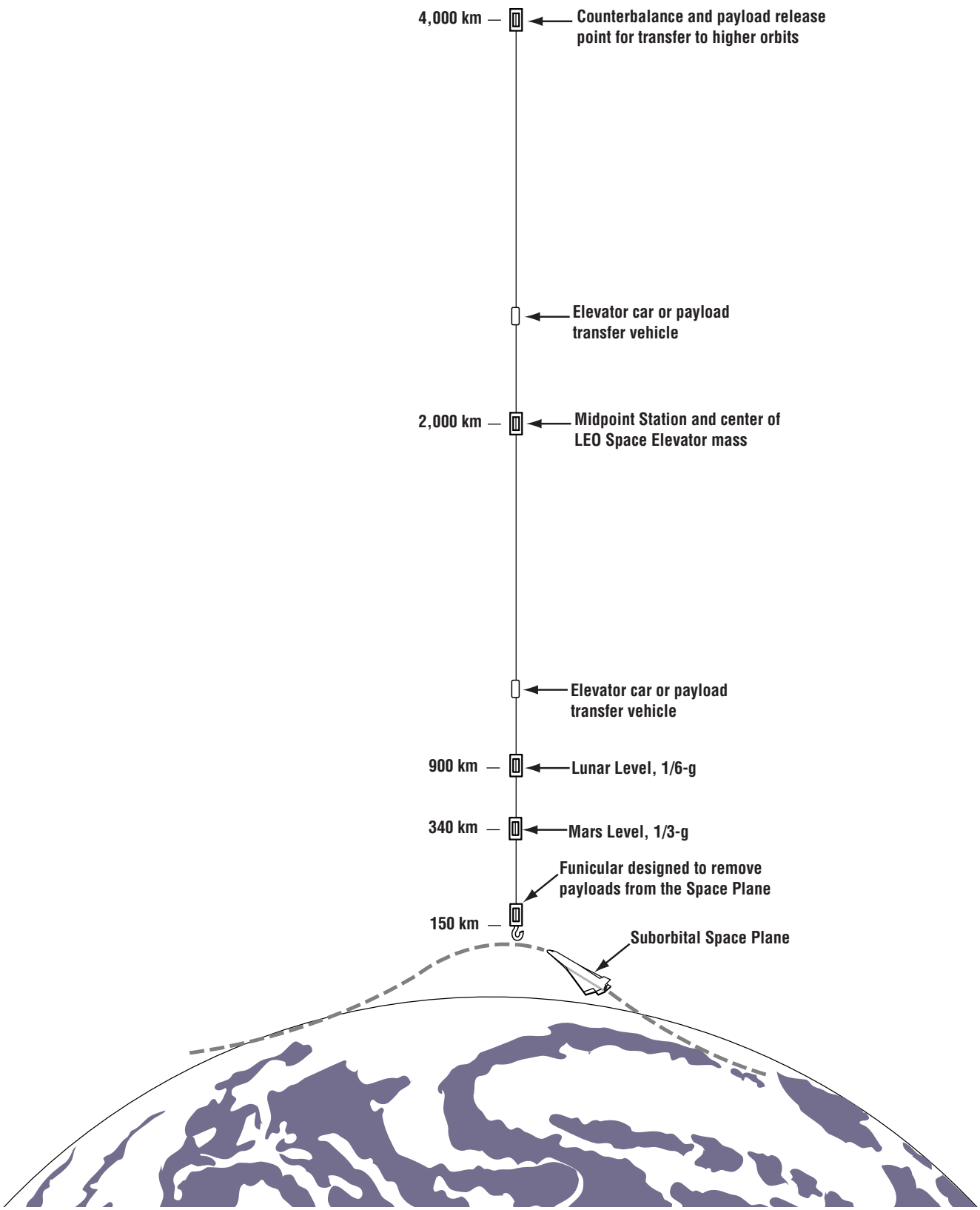


Figure 4. LEO space elevator concept.[9–11]

toward the center of the Earth and a second cable up so that it points away from the Earth. The bottom end of the lower cable hangs down to just above the Earth's atmosphere such that a future space plane flying up from the Earth's surface would require ≈2.5 km/sec less change in velocity (ΔV) than a single-stage-to-orbit (SSTO) vehicle launched directly to LEO. The space plane and LEO space elevator combination would likely be able to carry 10 to 12 times the payload as an equivalent-sized SSTO launch vehicle without the LEO space elevator. The length of the upper cable is chosen so that its endpoint is traveling at slightly less than Earth escape velocity for its altitude. This is done so that a spacecraft headed for higher orbit, the Moon, or beyond, can be placed in the proper orbit with only minimal use of its onboard propellant.

The overall length of a LEO space elevator from the bottom end of its lower cable to the top end of its upper cable is anywhere from 2,000 to 4,000 km, depending on the amount of launch vehicle ΔV reduction desired. For example, a 2,200-km-long system provides a 1.6-km/sec reduction in launch vehicle ΔV, while a 3,000-km-long system gives a 2-km/sec reduction, and a 3,800-km-long system offers a 2.3-km/sec reduction. It should be possible to launch a LEO space elevator in segments using existing launch systems. Once on orbit the LEO space elevator would then use its own onboard propulsion system to raise itself to the necessary orbital altitude while reeling out the upward and downward pointing cables as it went. Another advantage of this system is that as the market expands and materials improve, it could continue to grow in length and diameter, further reducing launch ΔV and increasing system payload capacity. It even appears possible to grow the LEO space elevator into the full-length, 35,000-km-plus space segment length of the Earth surface to GEO space elevator if that were desired.

The concept illustrated in figure 4 is a long, freely orbiting, vertically oriented tether structure that completes 12 orbits per day. The fact that it is a freely orbiting system and not attached to the Earth at its lower end allows the system to be placed in an inclined orbit aligned with the plane of the ecliptic. This has advantages for traveling to the Moon and other planets as it would avoid plane change maneuvers and would greatly increase the number of launch windows for a given timeframe (fig. 5). Another advantage of the inclined orbital plane is that if a resonant orbit is used, the lower end of the system will pass within range of most of the world's major airports twice a day on a fixed schedule. Once the velocity required to reach the lower end of the LEO space elevator is down to the Mach 16 range or less, horizontal takeoff and landing space planes operating out of those airports appear to become both technically and economically feasible.

Another possibility is to combine the LEO space elevator with a vehicle utilizing an Earth-based electromagnetic launch rail or mass driver. Due to the size of the investment required to build a ground accelerator of this size, it would most likely require the higher flight rates made possible by an equatorial orbit and an equatorial launch site in order to make such a large, high-speed ground accelerator economically viable. A variation on this idea would be to use a vertically oriented, 4g ground accelerator mounted on a 4.5-km-tall tower to accelerate a launch vehicle to ≈600 m/sec as a way of further reducing the launch vehicle's ΔV requirements and increasing its payload fraction. In this way it might be possible to keep the cost of the ground accelerator down to an amount that would be profitable at a much lower flight rate, thereby allowing the LEO space elevator to be in a resonant orbit in the plane of the ecliptic.

In addition to allowing spacecraft leaving the upper end of the cable to be released at near Earth escape velocity, people traveling to the Moon or Mars would be able to experience those gravity levels on the LEO space elevator prior to departure. A station located at ≈340-km altitude would experience Mars' gravity levels while another station at 900-km altitude would be at a gravity level similar to the Moon. These stations would also be good for people returning to Earth from long stays in low or zero gravity as they would allow them to gradually reacclimate themselves to full Earth gravity. The Earth arrival/departure terminal at the bottom of the lower cable is at about one-half Earth gravity (fig. 4).

There are three major issues associated with LEO space elevator operations that will require some type of propulsion system included in the design. These are atmospheric drag caused by the lower end of the cable, movement of payloads up and down the cable, and changes to the system's center of gravity and orbital altitude that are the result of arriving and departing spacecraft.

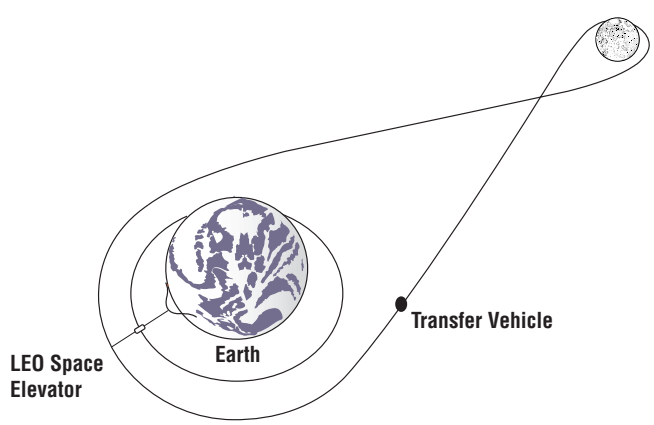


Figure 5. LEO space elevator for lunar transfers.

The majority of the atmospheric drag is caused by the lower end of the cable between the lower endpoint station at 150-km altitude and the Mars station at 340-km altitude. In the example shown (fig. 4), a unit payload of 5 metric tons in a 12-orbit-per-day system using T–1250 graphite fibers, a fiber volume of 65 percent, and a safety factor of 2.5, the diameter of the lower cable segments will be on the order of 6 mm. This produces a continuous drag force of ≈10 N for the cable and an additional 2-N drag when a payload is transiting this segment of the cable. Because of the near-exponential dependence of air density on altitude, and the large area of even a thin tether, most of the drag on a long tether system is caused by the lower 30 km of the tether itself. Hence, hoisting the lower end up a modest amount between uses can greatly reduce average drag. One way to do that is to use a "funicular" at the bottom, a car at either end of a long rope, so they somewhat counterbalance each other. Between uses the cars can be stored at intermediate heights, while during use the lower one reaches down to 150-km altitude.

Movement of people and cargo to various locations on the LEO space elevator will be via elevator. These mass movements will cause the LEO space elevator's center of gravity to move, and as a result, change the system's orbital altitude. The arrival and departure of spacecraft will cause even greater changes in the center of gravity. Consequently, it will be necessary to constantly "fly" the LEO space elevator to maintain its orbital altitude within a certain range. The smaller of these center of gravity movements may be dealt with by raising and lowering the upper and lower endpoint terminals and with local adjustments of the midpoint station. Large center of gravity changes will require a propulsion system on the LEO space elevator to raise or lower its orbit. In the cases of launch vehicle arrivals from Earth, departures of a spacecraft to the Moon or higher orbits, or transfers of a large payloads cargo up the cable, it will be necessary to use the propulsion system to speed the LEO space elevator up and raise its orbit. In the cases of lunar arrivals, departures to Earth, or large payloads moving down the cable, it will be necessary to use the propulsion system to slow the LEO space elevator down and lower its orbit. Sizing of the propulsion system will be determined by the amount of center of gravity travel and the flight rate. Lower flight rates will allow more time between arrivals and departures, thereby allowing for a smaller, lower thrust propulsion system, while higher flight rates will require a larger, more powerful system. As the system matures and the mass flow moving down the cable matches the mass flow moving up the cable, the propulsion system will only be needed for drag makeup.

There are two prime candidate technologies for this propulsion system: ion propulsion and electrodynamic tether propulsion. Electrodynamic tether propulsion[12] is unlike most other types of space propulsion in use or being developed for space applications today. There are no hot gases created and expelled to provide thrust. Instead, the environment of near-Earth space is being utilized to propel a spacecraft via electrodynamic interactions. A charged particle moving in a magnetic field experiences a force that is perpendicular to its direction of motion and the direction of the field. When a long conducting tether has current flowing through the cable, this force is experienced because charged particles are moving along the wire in the presence of the Earth's magnetic field. This force is transferred to the tether and to whatever is attached to the tether. It can be an orbit-raising thrust force or an orbit-lowering drag force, depending on the direction of current flow. Putting current into the cable makes it an orbit-raising thrust while drawing current from the cable makes it into an orbit-lowering drag force. The principle is much the same as an electric motor; reverse its operation and it acts as a generator. The principle advantage of this propulsion system over any of the other types of propulsion systems (including ion) is the lack of any need for a propellant to serve as a reaction mass. In other words, solar arrays may be all that is needed to produce the energy required. This means lower recurring cost. Today, large-scale reboost by electrodynamic tether is not a proven technology, but a technology demonstration is being developed and will be tested on orbit in the near future.[13]

3.2.2 Momentum Exchange Tethers

Another near-term concept for space transportation that is related to space elevator technology is the momentum exchange tether. Rotating tether transportation stations located in Earth, lunar, and Mars orbits have been proposed for payload transfer between points in space as well as from the planetary surface to space (fig. 6). Some of these concepts for rotating tethers are quite complex but could be developed in stages as a means for transfer of payloads from one orbit to another. In one scenario a rotating tether in lunar orbit reaches down to the surface of the Moon to drop off and pick up payloads. The payload is then captured in a high-Earth orbit and passed down to another elevator in LEO. Innovative facilities like this will help develop the infrastructures in space needed for future space elevator developments.

3.2.3 Lunar Space Elevator Concepts

Another near-term application of the space elevator concept could be demonstrated at the Moon. The one-sixth gravity at the Moon makes it theoretically possible to construct tethered connections from the surface of the Moon to the lagrange libration points L1 and L2, on the near and far side, respectively, using existing materials (Kevlar, Spectra, or PBO graphite epoxy).[14]

It has been envisioned that on the near side of the Moon such a structure could become the transportation system for

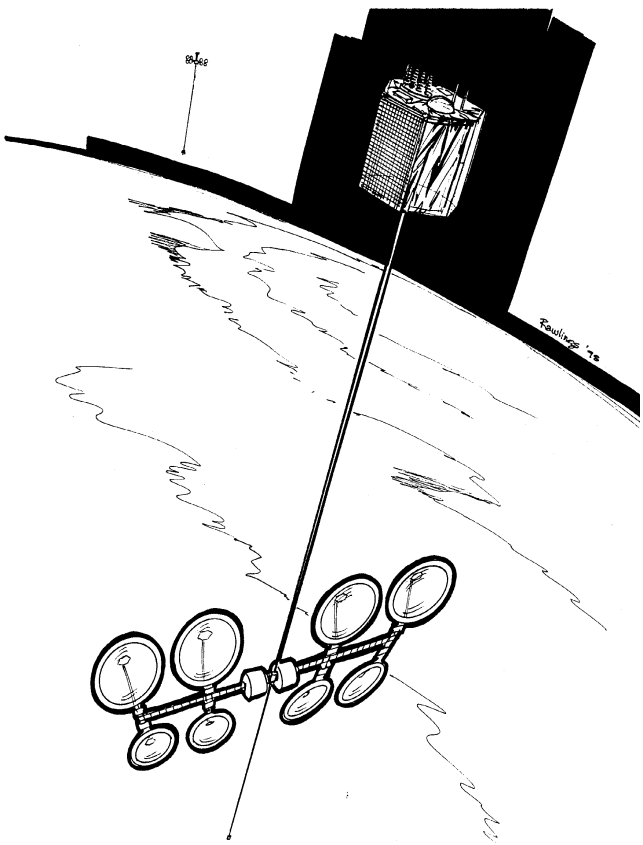


Figure 6. Momentum exchange facility.[15] This orbital transfer station uses a rotating momentum exchange tether system to transfer payloads to higher orbits. An electrodynamic tether propulsion vehicle is shown over the horizon.

moving materials to L1 in support of solar-powered satellite construction and propellant storage platforms. The regolith located at the base of the elevator contains oxygen which could be extracted. Additional gases from ice deposits at the lunar poles might also be transported around the Moon to this point for transfer to L1. At L1, solar-powered satellites would become part of a space utility system for production and transfer of power to the surface of the Moon and other stations within the Earth/Moon system. Likewise, a propellant platform at L1 would act as a service station for reusable in-space transportation vehicles.

On the far side of the Moon at L2, a similar system could be envisioned for lunar and space infrastructure support. On the surface of the far side of the Moon, ideas have been proposed for large space observatories, and as a remote location for the long-term storage of hazardous materials like the nuclear waste generated on Earth that must be stored safely for thousands of years. Figure 7 illustrates the concept for a tethered satellite at the Moon as well as the other concepts discussed within the Earth/Moon system.

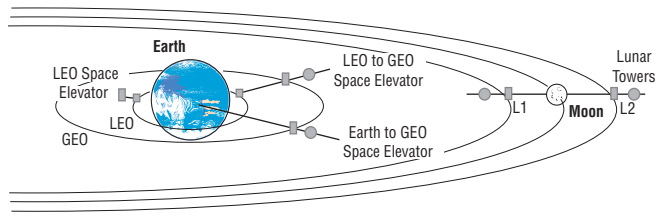


Figure 7. Earth orbiting and lunar space elevator concepts.

3.2.4 Mars Space Elevator Concepts

At Mars, proposals have been studied for tethered elevator type structures in a low-Mars orbit, and extended from the two moons in orbit around the planet, Phobos and Deimos. Both moons are in the same orbital plane around Mars at near equatorial inclinations. Tether structures extended toward and away from Mars on each of these moons have been shown to provide a means of payload transfer to and away from Mars that would significantly reduce propellant requirements (fig. 8).

The material strength required for a system like this appear to be within the limits of current technology. In one possible design, a Kevlar tether is used to transfer a 20,000-kg payload from a low-Mars orbit to a Mars-Earth transfer orbit.[16] Such a system in orbit around Mars could be one way to establish a permanent transportation infrastructure for ongoing exploration and development of the Mars system.

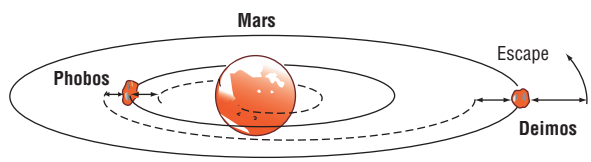


Figure 8. Mars space elevator transportation system.

3.2.5 Applications for Tension Structures

There are many other missions and infrastructure developments that are related to tension structures that could help develop the technologies needed for space elevator construction. Ideas for these developments were compiled and are listed as follows; many are related to the current *International Space Station* (*ISS*) program:

- Tethers for remote rendezvous and capture of unproven commercial vehicles at the *ISS*

- Orbital tethers using electrodynamic propulsion demonstrating incrementally longer lengths (i.e., 10, 50, 250, 1,000 km, etc.)

- Tethered mass at *ISS* for center of gravity control
- Electrodynamic reboost for *ISS*
- Tethers to drop payloads and expendable materials from *ISS*
- Tethers attached to *ISS* for remote storage and transfer propellants
- Tethers to demonstrate *ISS* towing with the Space Shuttle
- Electrodynamic tethers for magnetic braking at Jupiter and power generation on exploration spacecraft
- Tapered tethers for long suspension bridges
- Lighter weight cables for construction and mechanical systems.

As high-strength materials are introduced into commercial markets, there will be more applications that are not possible to envision today. Technology development and growth in this market will help make long-term development of space elevators possible.

3.3 Compression Structures

The third technology area is in the continued development of tall towers for Earth applications, and eventually for space applications. This requires the introduction of lightweight composite structural materials to the general construction industry for the development of tall tower and building construction systems. The goal is to foster the development of multikilometer-height towers for commercial applications (i.e., communications, science observatories, and launch platforms).

3.3.1 Tall Towers

Today, the world's tallest self-supporting building is the CN Tower in Toronto, Ontario, Canada. It was built from 1973–1975, is 553 m in height, and has the world's highest observation deck at 447 m. The tower structure is concrete up to the 447-m observation deck level. Above the observation deck is a steel structure supporting radio, television, and communication antennas. The total weight of the tower is ≈300,000 tons. The height of existing towers and buildings today are not limited by construction technology or by materials strength. Conventional materials and methods make it possible even today to construct towers many kilometers in height. When considering how high a tower can be built, it is important to remember that it can be built out of anything if the base is large enough. Theoretically, you could build a tower to GEO out of bubble gum, but the base would probably cover half the sphere of the Earth. The height of existing towers and buildings today are not limited by building technology or by materials strength; it is simply that there has not been a good economic reason to build towers any taller than have been built so far.

One approach in determining the maximum height practical for various tower construction materials is to look at the maximum height of a column that can just support its own weight. This is done by dividing the column materials' strength by its density (strength ksi/density lb/in.^{3} = height in inches). The two most common tower construction materials yield the following results:[17]

Structural steel = 60 ksi/0.3 lb/in.^{3} = 200,000 in. = 5 km theoretical

Aluminum = 60 ksi/0.1 lb/in.^{3} = 600,000 in. = 15 km theoretical.

If new composite materials were introduced to the conventional construction industry, then even greater heights would be possible. Using the same analysis yields the following result:

Carbon/epoxy composite = 300 ksi/0.066 lb/in.^{3} = 4.5×10^6 in. = 114 km theoretical.

Real designs will use a lower design stress and have structural overhead for horizontal members to provide stability and strength against buckling. Instead of a single column, it will be a tapered tower with a height-to-base width ratio of 20 (i.e., a 20-km-tall tower would require a 1-km-wide base). By increasing the base width and distributing the load of the upper sections over more area and more members in the lower sections, then even taller tower heights are conceivable. An approach to this type of tower construction is illustrated in figure 9.

This tall tower concept (fig. 9) uses a fractal truss design with the main columns made up of smaller trusses, which in turn are made of smaller trusses. This approach minimizes wind load, provides reasonable component sizes, and would lend itself to a robotic assembly method. For stability against buckling, the height-to-base width ratio of 20 is used.[17]

3.3.2 Pressurized Tower Concept

One of the most fundamental problems with high-strength materials is that they are typically stronger in tension than in compression. For example, the strongest compression material readily available is boron/epoxy, capable of supporting its own weight up to 122.5 km in height. Whereas, the strongest tensile material readily available today is PBO graphite epoxy, a high-strength polyaramid fiber capable of supporting its own length up to 373.8 km. What is needed is a way to convert tensile strength into compressive strength.[6]

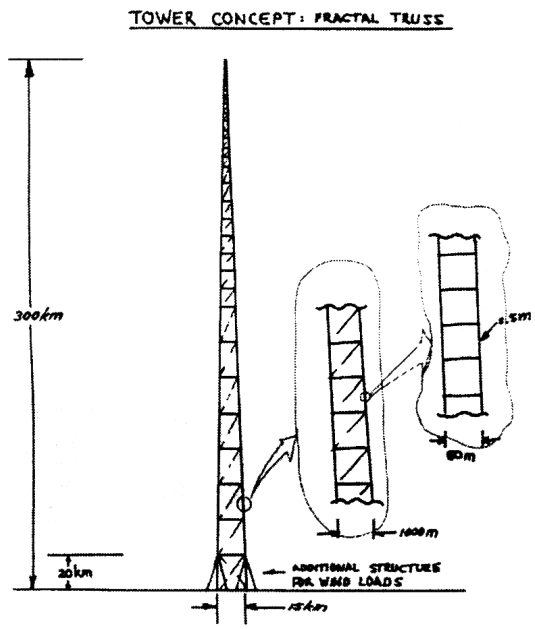


Figure 9. Tall tower concept.

The pressurized tower concept is a way to do this—convert tensile strength of materials into compressive strength. Consider a balloon as an example. The rubber fabric has tensile strength, but falls flat under compression from its own weight. Once inflated, the air pressure inside the balloon converts the structure into a pressurized shell capable of withstanding both tension and compression loads.

By converting tensile strength into compressive strength with a pressurized shell, PBO fibers can be used to build towers many times taller than would otherwise be possible. For example, a tower 3,000 km in height is theoretically possible using PBO fiber, and it would still be less massive than the CN Tower. The tower would be constructed in segments with bulkheads to keep the pressurized gas from migrating to the bottom of the tower. Increased loads toward the bottom can be supported by increasing the pressure in the lower sections or by increasing the cross-sectional area of the gas.[6]

A problem with a tower of this height is failure through buckling. Although the PBO fiber materials in combination with a pressurization system can likely handle the compressive loads, some type of active stabilization system would be required to keep the tower vertical. Today, many tall buildings include active control systems to control movement from high winds and earthquakes. These systems provide sway control for additional comfort in high winds and stabilization during earthquake emergencies. However, no tall buildings or structures have been built with their basic structural integrity dependent on an active system.

3.3.3 Tall Tower Applications

Tall towers that extend up through the Earth's thick atmosphere appear to have numerous applications for government and commercial purposes and appear to be feasible in the near term from a materials capability standpoint. Two concepts illustrated in this section help explain the wide variety of uses that tall towers could perform.

Figure 10 illustrates a tall tower concept 50 km in height constructed from composite materials. Its primary use is to launch payloads from a rotating tether to LEO or to a LEO space elevator shown over the horizon. Other uses for towers of this height include the following:

- Communications boost: A tower tens of kilometers in height near large metropolitan areas could have much higher signal strength than orbital satellites.
- Observation platform: A permanent observatory on a tall tower would be competitive with airborne and orbital platforms for Earth and space observations.
- Solar power receivers: Receivers located on tall towers for future space solar power systems would permit use of higher frequency, wireless, power transmission systems (i.e., lasers).
- Drop tower: Tall towers several tens of kilometers in height could provide several minutes of free-fall time for microgravity science experiments.
- Deep sea platforms: Tower construction technology of this magnitude means it would be possible to support deep sea platforms from the ocean floor even to the maximum depth of the ocean at 11 km.
- LEO communications satellite replacement: Approximately six to ten 100-km-tall towers could provide the coverage of a LEO satellite constellation with higher power, permanence, and easy upgrade capabilities.

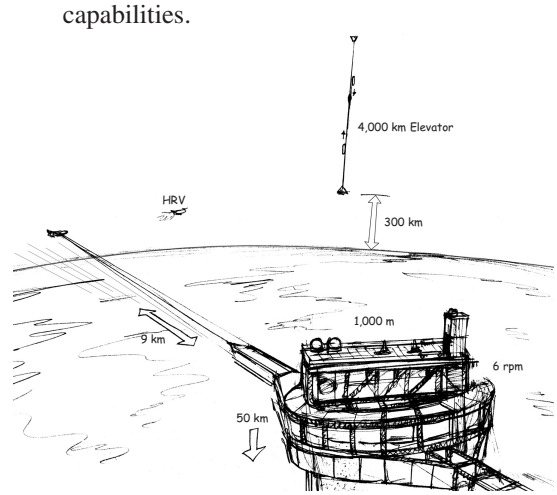


Figure 10. High-altitude multipurpose tower concept.[5]

Figure 11 illustrates a launch arch concept that uses a series of tall towers in combination with an electromagnetic launch assist rail. At 15 km in height, this system has the potential to significantly improve the performance of future reusable launch vehicles by providing a permanent first stage and by launching above 83 percent of the Earth's atmosphere.[18]

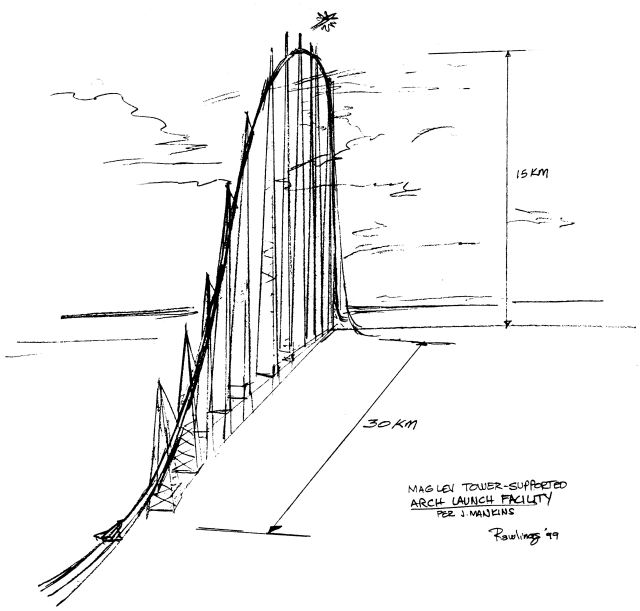


Figure 11. Launch arch concept.[5]

Other potential uses for such a system include the following:

- Variable-gravity (g) launch: A rail designed for low-g launch assist could use a similar configuration designed for high-g launch. Propellants and raw materials could be delivered to LEO with minimal upperstage requirements.

- Entertainment: Tourism to the edge of space where passengers could see the darkness of space and the curvature of the Earth's horizon.

- Bridge construction: Material and construction technology development for larger bridge span developments.

Advantages of these types of structures include lower gravity, no weather-related interference, accessibility to upgrade of mounted systems, and permanence. These features over the long term could provide significant economic advantages over conventional launch systems and some LEO satellite systems. Many other ideas that have yet to be envisioned are always possible from new technology developments like this.

3.4 Electromagnetic Propulsion

The fourth technology area is in the continued development of electromagnetic propulsion systems. Electromagnetic propulsion is important to the space elevator concept because of the need for a high-speed, noncontact transportation system to quickly traverse the space elevator's great length. Technology development would include the application of electromagnetic systems to a variety of transportation systems including MagLev for propulsion of trains, MagLifter for launch assist of new, reusable launch vehicles, and mass driver and rail gun systems for propulsion of payloads to orbit at high-g levels.

3.4.1 Elevator Climbing Mechanisms

Mechanical mechanisms are in existence today for elevators in tall buildings. The problem with these systems is that they are mechanical, and require cables and guide wheels in contact with supporting rails in order to climb the structure. This type of system may be used for the space elevator, and may well be the only way to climb the elevator during its construction phase. The purpose for exploring electromagnetic technology for the elevator is to develop a means by which vehicles can climb up and down the elevator without contacting the structure or guide rails. This would then lend itself to a system that would be very low maintenance on both the vehicles and the structure, and potentially very fast. High-speed systems in the thousands of kilometers per hour are desirable due to the great length to be traveled in space. Another reason for the pursuit of an electromagnetic system is a concept for energy recovery. Energy is used during the initial lift and acceleration phase up the elevator. With an electromagnetic system there is the potential that electrical energy could be recovered in the braking phase to slow the vehicle down. An energy management system that recovers and reuses this energy could make the total system very energy efficient.[19]

One analysis determined that the energy required to climb the space elevator from the ground to GEO would be ≈60 MJ/kg. If an energy system were used equivalent to the *ISS* solar arrays producing ≈60 W/kg, it would take ≈12 days to climb the structure at an average speed of 125 km/hr. This is the type of system that would be anticipated for a conventional elevator for construction, maintenance, and repair. An operational system needs higher power levels to reach the higher speeds that have been demonstrated by electromagnetic sleds. To reduce the travel time to ≈10 hr, a power level of ≈1 kW/kg would be needed, resulting in speeds of ≈2,000 km/hr. Figure 12 is a vision vehicle for the space elevator representative of this type of high-speed transportation system.

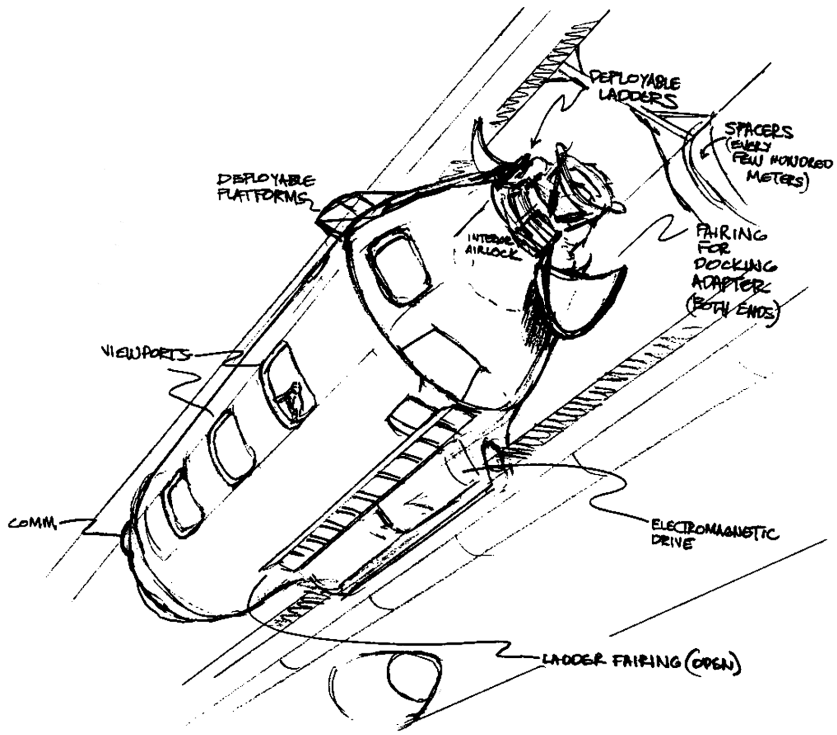


Figure 12. Concept for a high-speed electromagnetic propulsion vehicle for the space elevator.[5]

There are several intermediate steps that can be taken toward reaching this level of technology. These have been grouped into low-g and high-g systems as follows.

3.4.2 Low-Gravity Systems

Low-g systems are for human-rated vehicles that have accelerations up to ≈3-g (3 Earth gravity levels). Two concepts for use of electromagnetic propulsion in low-g systems are the MagLev for magnetically levitated train systems, and the MagLifter for magnetic lift to provide launch assist for space launch vehicles.

MagLev systems are in operation today as people movers at several airports in England. These vehicles are levitated and propelled through electromagnetic systems at ≈40 km/hr. High-speed test vehicles for large trains have been under development for many years in the United States, Germany, and Japan. Some of these vehicles have achieved speeds >500 km/hr. The tracks for these high-speed vehicles are very precise engineering achievements utilizing electromagnetic levitation, or in some cases, permanent magnets that require no lift energy at all. Other vision vehicle systems have included concepts for integrating both automobiles and trains into a common electromagnetic track system such that they can transition from one to the other (fig. 13). The potential for MagLev systems is to accelerate ground transportation up to speeds equivalent to airline travel.

MagLifter uses the same technology to achieve even higher speeds for launch assist. The concept is to create a high-speed sled that can accelerate and release a launch vehicle at a high altitude. This is the concept for the launch arch illustrated in figure 11. The long MagLifter track acts like a fixed, reusable first-stage facility that gives the vehicle its initial launch velocity to orbit.

In the MagLifter concept illustrated in figure 14, a superconducting magnetic levitation sled is used to accelerate an SSTO vehicle to a velocity of ≈1,000 km/hr. The vehicle is then released from the sled and proceeds to LEO as a conventional SSTO vehicle. This concept seeks only to provide a small portion of the total Earth-to-orbit ΔV. The MagLifter does not require very high accelerations. It combines a long acceleration length and modest exit velocity to achieve aircraft-like operations. MagLifter advances MagLev technology, which is relatively mature and has many terrestrial transportation applications.

3.4.3 High-Gravity Systems

High-g systems are for nonhuman payloads that can survive high accelerations in the hundreds and thousands of gees. Two concepts for high-g propulsion systems are the rail gun and the mass driver (or coil gun). Please note that both systems deliberately use gun terminology in their descriptions because the resulting launch velocities from the end of their tracks are at velocities equivalent to projectiles fired from a gun or cannon.

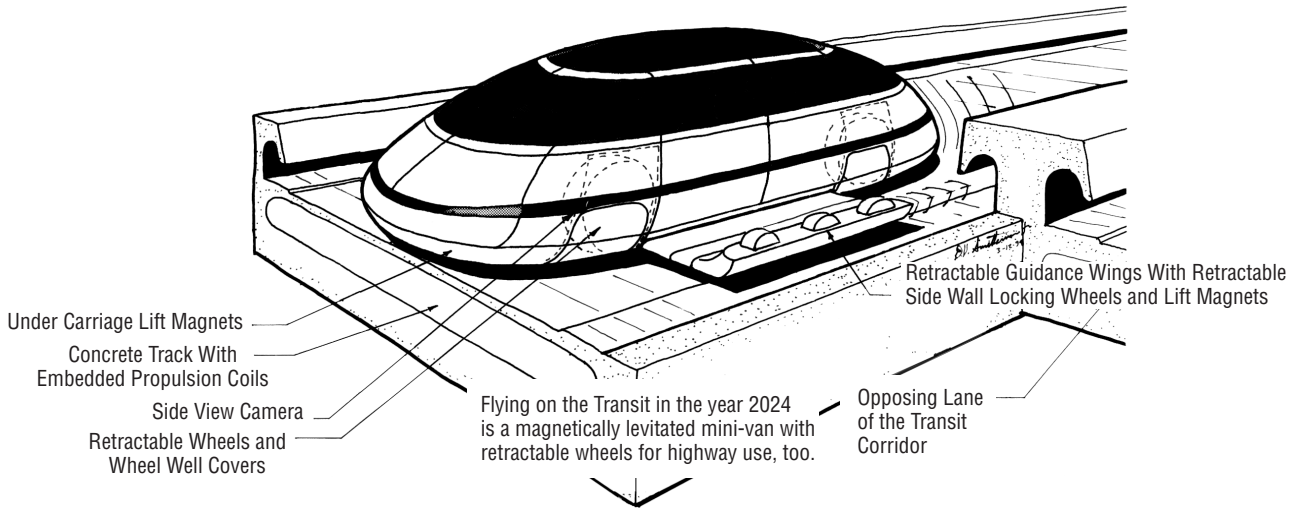


Figure 13. A MagLev concept called Transit used for both trains and van-sized vehicles.[20]

Conceptually, the rail gun, shown in figure 15, may be the simplest type of electromagnetic launcher because it is identical to a linear direct current motor. A current flows between linear stators (rails) that extend the length of the barrel, through an armature that moves along and between the stators, and exits the gun at the muzzle. The current flows between the stators and the armature through brushes so the armature can be a conducting solid, but for very high velocities it must be a plasma gas. The armature and its attached payload is accelerated by the Lorentz force which is proportional to the current and to the magnetic field generated by the current. Therefore, the force is proportional to the square of the current. Moderate efficiencies, on the order of 40 percent for near-term applications and perhaps 70 percent for far-term systems, are theoretically possible with rail guns.

Demonstrated rail gun performance ranges from muzzle velocities of 4.2 km/sec (15,120 km/hr) with masses of several hundred grams to 11 km/sec (39,600 km/hr) for a 2.8-gram load at accelerations of 50,000 to 200,000 gees. Although significant research has been done on rail guns, there has been limited success at development of a practical device. Current devices are limited to a single shot per rail set due to rail erosion or outright structural failure due to the strong forces involved in their operation. For example, the 2.8-gram, 11-km/sec result given above corresponded to the fragments of a projectile that exited the rail gun after a test in which the device was destroyed. Although a weapons application finds acceptable performance in a 1-kg, 10-km/sec projectile, there are serious concerns about scaling up in size to projectiles >50 kg for space launch payloads.[3]

Also shown in figure 15, a coil gun or mass driver operates through an inductive reaction between stationary stator coils and a coaxial conducting armature. The useful payload is attached to and accelerated by the armature, which can be a simple thick-walled aluminum cylinder. A large number of stator coils are stacked to form a kind of gun barrel; however, because there are no gases or vacuum arcs involved, no seals or gas-dynamic forces need be considered. When a coil is energized with the armature inside, the rising magnetic field induces a circular current in the armature and the interaction of the induced armature current with the radial component of the coil magnetic field is what drives the armature forward. The series of coils are energized sequentially by computer-triggered switches and capacitors, thus accelerating the armature to ever-increasing velocities.[3]

The major advantage of coaxial accelerators lies in their high efficiencies (>90 percent if a superconducting bucket coil is utilized) and the possibility of reusing the projectile bucket through deceleration by changing the polarity of the drive electromagnets. The high electric efficiency is mostly due to the oscillatory energy discharge from the storage capacitors. They are recharged virtually automatically, with the "lost" energy (imparted to the projectile as kinetic energy) showing up as a lower voltage across the drive capacitors. The reusable buckets give the advantage of significantly reducing the cost per shot. Also, unlike rail guns, coaxial accelerators can easily be scaled for large payloads.[3]

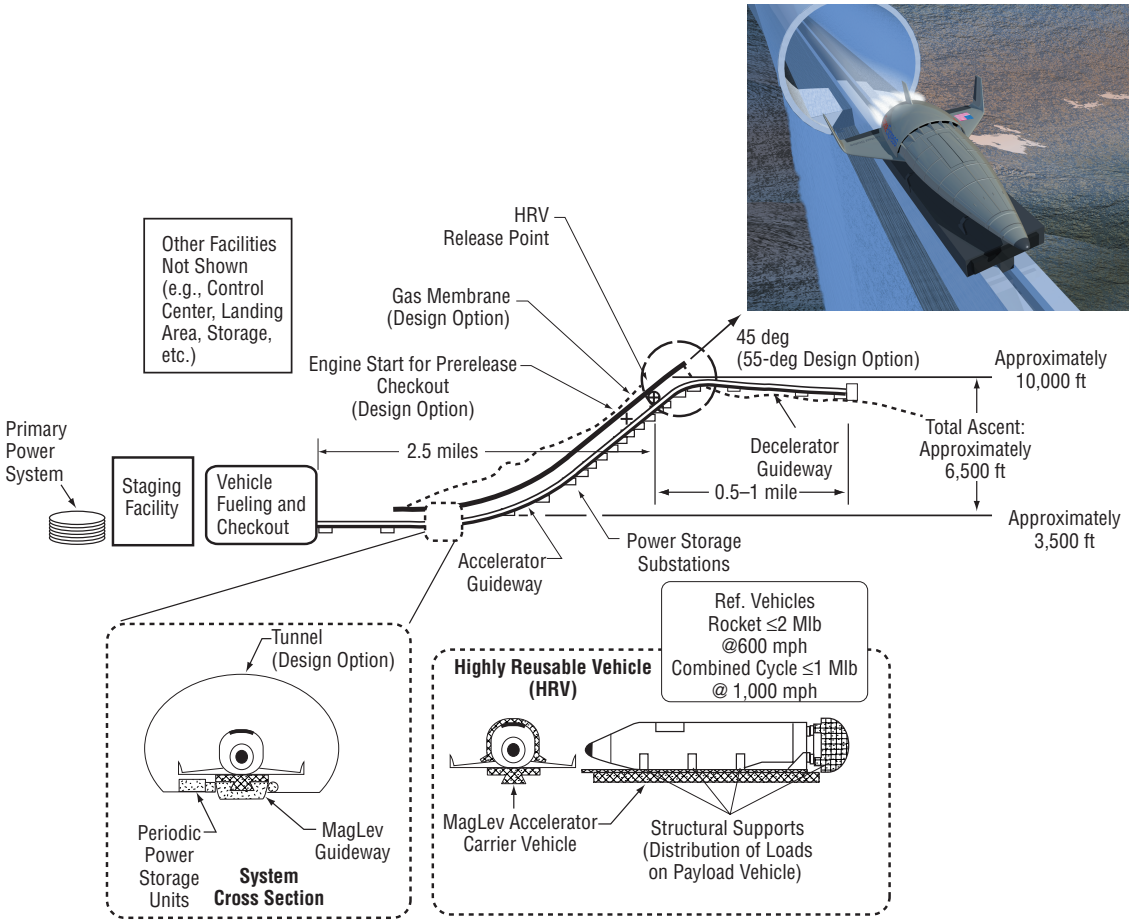


Figure 14. MagLifter launch assist concept.

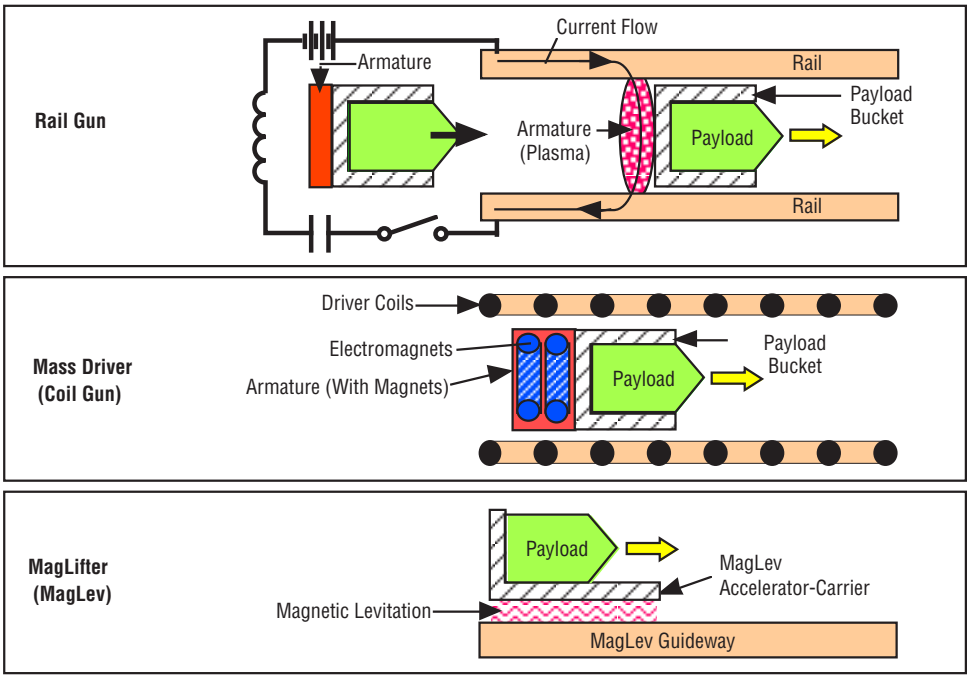


Figure 15. Electromagnetic launch systems.[1]

To date, only very small laboratory demonstration coil guns have been built. For example, a 135-gram aluminum sleeve was accelerated to a maximum of 250 m/sec (900 km/hr) and a 339-gram projectile was accelerated to 410 m/sec (1,476 km/hr). Thus, the only demonstrated devices have been small, low-velocity, laboratory-scaled devices. None of the scaled-up issues have been addressed experimentally. To be a practical launcher (or electric propulsion "thruster"), a coil gun will be an inherently large and complex device requiring rapid switching of large amounts of power. For example, a coil gun for a 10-ton projectile would require switching electric power at several hundred kilovolts in the stator electromagnets. This implies either a large, dedicated power plant or a significant energy storage system (e.g., capacitors). High-temperature, superconducting electromagnets may find an attractive application in coil guns, but this has not been demonstrated.[3]

It is not yet evident which of the electromagnetic systems described above would be best suited for the space elevator or exactly how any of them could be integrated into a space elevator structure that needs to be as light as possible. Low-g acceleration is needed as described for the MagLev and MagLifter systems, high velocities would be desirable as demonstrated by the rail gun developments, and energy recovery for highly efficient operation is desirable as described for the coil gun experiments. Continued development and application of this technology is needed for future space elevator developments.

3.4.4 Applications of Electromagnetic Technology

In addition to the use of electromagnetic devices for ground transportation and launch systems, other possible applications were identified as follows:

- Vertical MagLev for very fast elevators in tall buildings
- Lightweight rails and electromagnetic devices for launch towers and flight vehicles
- Electromagnetic devices for many conventional movable systems like doors, windows, partitions, etc.

3.5 Supporting Infrastructure

The fifth technology area is in the development of space infrastructures that will facilitate a growing economy in space to support construction of large systems like the space elevator. Today, our progress in space development is restricted to single projects of limited scope in LEO. Significant expansion of space infrastructure will be necessary to create the economic base and the construction capabilities needed for major developments beyond LEO.

3.5.1 Space Transportation Systems

A mature space transportation system from Earth to GEO will be needed to facilitate space elevator construction. This includes launch systems from Earth to LEO, in-space transfer systems from LEO to GEO, and transportation support facilities from Earth to GEO. These transportation systems should not be built exclusively for space elevator construction. The space elevator concept will only be successful if it is done in support of a growing economy in space where people are actively working to make this new frontier their permanent home. As such, the transportation systems must be multipurpose and highly reusable to support frequent flights comparable to today's airline and ground transportation systems.

Launch systems from Earth to LEO could include a wide variety of suborbital, launch assist, and SSTO vehicles. The MagLifter vehicle illustrated in the previous section with electromagnetic launch (fig. 14) is one concept that may be able to meet the kind of operational demands anticipated. Other systems derived from current X–33 and X–34 technology may be successful as well. Whatever the launch systems turn out to be, they must have safety and highly reusable characteristics for a wide range of cargo types, including people, as is found in today's conventional ground and air transportation systems.

In-space transfer systems from LEO to GEO will need to be safe and efficient as well. These systems could include vehicles that can be used as automated or human-piloted transfer vehicles for delivery of a wide variety of cargo and services within the LEO to GEO altitudes. New vehicles derived from current *ISS* propulsion and control module technology may be sufficient to create this capability; but, reusability will be key in making the system economically viable. Figure 16 illustrates a concept for a reusable transfer vehicle operating from a propellant storage and servicing platform in LEO. In this configuration, it is controlled with autonomous or remote systems for delivery of a satellite from the servicing platform to another location. Other uses could include delivery of people and cargo to GEO, human or remote servicing of spacecraft, and in-space construction of large space systems like the space elevator.

Another LEO to GEO transportation element could include rotating tether payload transfer stations as described in 3.2 Tension Structures. Figure 6 illustrated a momentum exchange facility that could be located at LEO and GEO to throw vehicles and payloads to nearly any orbital altitude or inclination. Such facilities may prove to be very efficient, when used with the reusable transfer vehicles and propellant platforms to grow a robust space transportation infrastructure, because they can provide delivery from LEO to GEO with the speed of chemical thrusters and the efficiency of electrical thrusters.

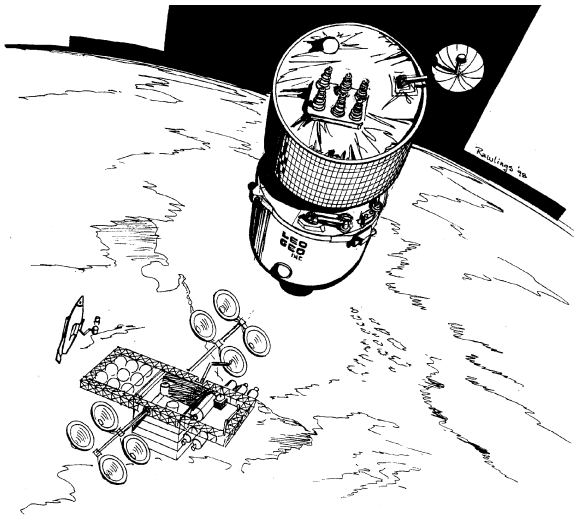


Figure 16. Reusable space transfer vehicle and propellant servicing platform.[15]

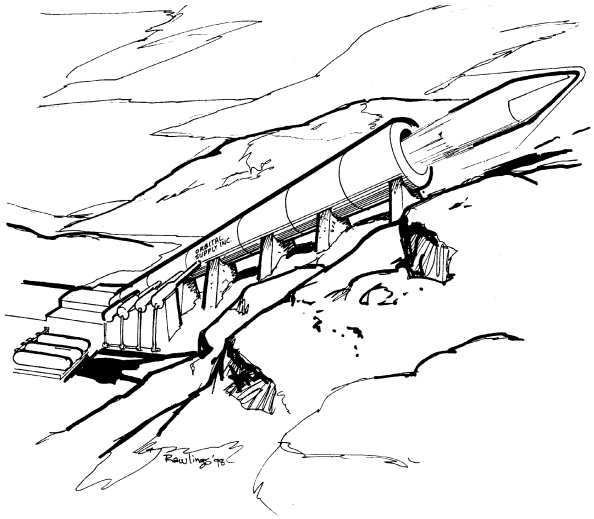


Figure 17. Electromagnetic gun launch system for delivery of raw materials to orbit.[15]

Finally, the ultimate LEO to GEO transportation system would be the precursor to the space elevator itself, the LEO space elevator, also described in 3.2 Tension Structures (fig. 4). The concept here is to begin with a LEO elevator and work toward expanding its length from LEO to middle-Earth orbit (MEO), and eventually LEO to GEO.

Transportation support facilities from Earth to GEO would include space stations and servicing platforms to support a growing economy in space. In support of the vehicles, stations, and platforms, a network of propellant production, delivery, and storage systems will be needed. This could include a fleet of tanker-type vehicles for propellant delivery, or the use of one of the electromagnetic launch systems described in the previous section for delivery of water and other raw materials to orbit for propellant production. Figure 17 illustrates a gun-launch concept for high-g delivery of raw materials to LEO as described in the previous section on electromagnetic propulsion. Cost-effective ways to deliver raw materials and finished products will be needed to support and stimulate continued economic growth in space.

The servicing platforms, storage facilities, and space stations to support human operations and developments from LEO to GEO can be derived from current *ISS* and TransHab technology (Transhab is a large inflatable habitat proposed for the *ISS*). It is likely that human activities on orbit will have to expand to include tourism and permanent residency in new space station-type facilities called space business parks before space elevator developments can be supported economically. Figure 18 illustrates a space business park derived from current *ISS* and TransHab technology for a variety of business ventures. Such facilities will produce new revenue from a variety of markets to grow and expand a new space-based economy.

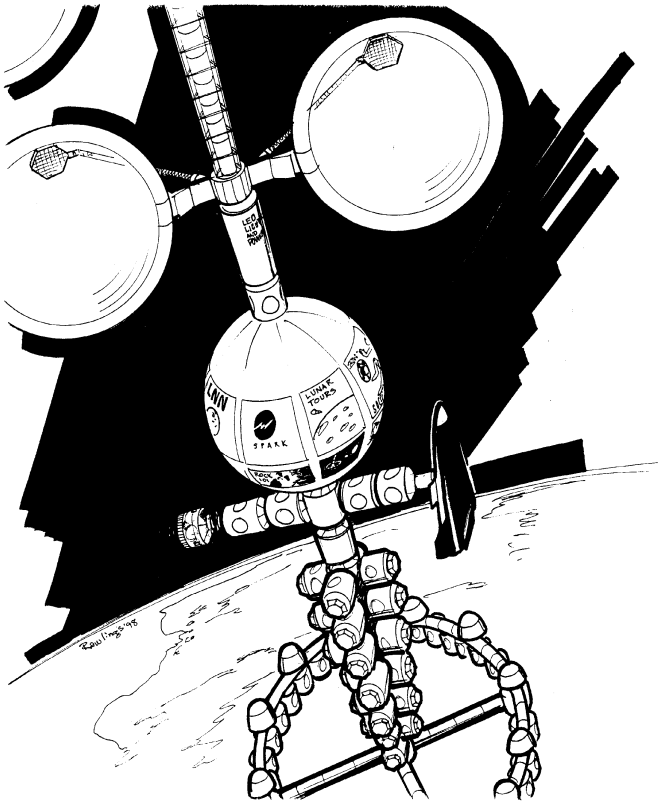


Figure 18. Space business park.[15] A multiuse space station facility for compatible businesses including tourism, sports, film production, and entertainment, as well as support to satellite services, research and development facilities, and on-orbit processing and manufacturing.

3.5.2 Space Solar-Powered Systems

Solar-powered systems in space are in common use today on the *ISS* and most Earth-orbiting satellites. There is an abundance of solar energy available, and technology work is in progress to improve the performance of these systems. As part of an overall orbital infrastructure, it is likely that space solar power as a utility system for space development will become an important element. In addition, space solar-powered systems have the potential to provide an abundance of clean energy to Earth-based utility systems. Technology development for collection and delivery of space solar power to Earth utility systems is in progress now and has the potential to lead to major developments in space in the future (fig.19).

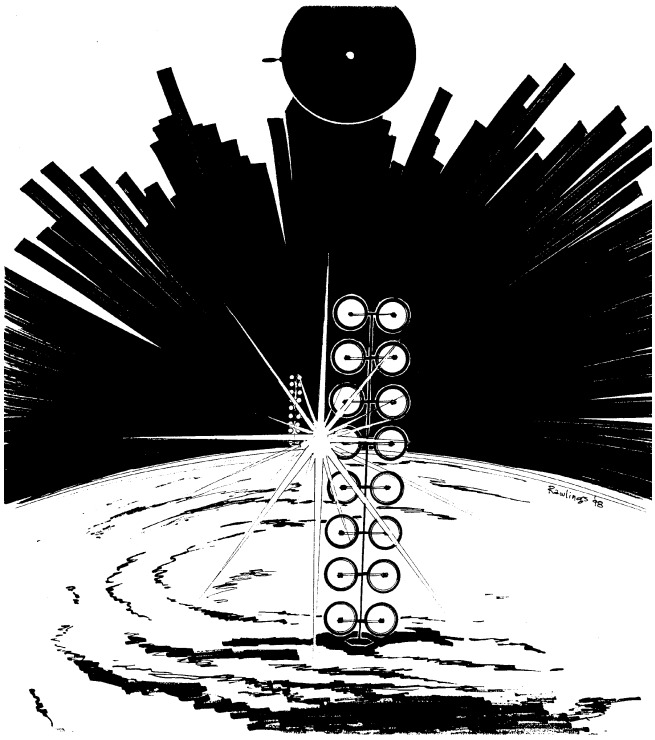


Figure 19. Space solar-powered satellite.[14]

For the space elevator, advances in the development of solar cell films may make it possible for the surface of the space elevator to become a solar collector. If, for example, the cover illustration for a space elevator included a covering of solar cell film around the central structural tube that exposed only 1 m of its width to sunlight along its entire length, then the elevator alone would have ≈36,000,000 m^2 of collection area.

Another interesting concept for space solar-power in relation to the space elevator is that the first Earth to GEO tether structure used to make the initial connection could be used as a direct power line. Initially, power would be delivered up the elevator for construction support at GEO, and later power would be delivered down the elevator to ground utility systems from solar-powered satellites stationed in GEO. This direct power line approach could prove to be more efficient than power beaming methods through the Earth's atmosphere. This idea is further supported by the findings described in 3.1 Materials, that carbon nanotubes now under development are electrically conductive. So it appears that at least one material that has potential for becoming the structural backbone of the elevator may also be used as a good power conductor for future space solar-powered systems.

3.5.3 Robotic Assembly, Maintenance, and Repair Systems

The space elevator and all of the infrastructure elements described in this section will require continued advances in robotics to support space assembly, maintenance, and repair systems. Figure 20 illustrates a concept for modular robotic free-flyers that can attach to the transfer vehicles illustrated in figure 16 for remote control construction operations. Development of standards to interface and communicate with these types of systems can be derived from current *ISS* systems where remote control of robotic systems is in extensive use. For the space elevator, it will be important that advances are made toward autonomous systems where the robot will recognize the assembly, maintenance, or repair condition, and proceed with the work accordingly. As noted in later sections on space environments and safety issues, autonomous systems that can make continuous repairs to the space elevator structure from micrometeoroid impacts will be critical to the success of the space elevator concept.

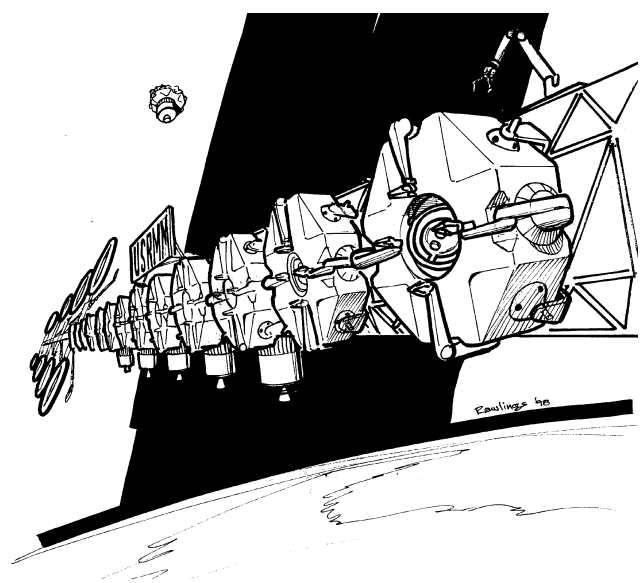


Figure 20. Modular robotic systems for space assembly, maintenance, and repair.[15]

The unique requirements for constructing a space elevator may create additional technologies related to robotic assembly, maintenance, and repair. The concept for assembly of the space elevator in this report described construction of a tall tower through the atmosphere joined to a tether structure suspended from GEO. This will call for high-altitude construction methods from the ground and perhaps some form of automated material processing, fabrication, and assembly of linear structures from GEO.

The tallest buildings and towers constructed today are assembled from either a crane anchored in the elevator shafts of the structure that are capable of lifting themselves up the structure as construction moves higher or multiple cranes that can lift each other up higher as needed. Occasionally, flying cranes (helicopters) are used as was the case for the CN Tower, the world's tallest building, where the top 102 m was assembled in sections weighing up to 8 tons. As towers reach higher and higher altitudes, new types of cranes, aerial platforms, and vehicles will be needed to support construction operations. For example, the launch arch (fig. 11) could use heavy-lift airships and high-altitude balloons for construction platforms and vertical transportation up the full 15-km height of the structure. Taller structures, like the 50-km launch tower (fig. 10), where little atmosphere exists, would require some form of vertical rocket-propelled platforms similar to the DC–XA technology developed for reusable rockets.

Once LEO altitudes are reached, there appears to be several options for construction of the space segment of the elevator from LEO to GEO, all of which will require extensive robotic systems. They include assembly in segments at GEO extending down to LEO, assembly at LEO extending up toward GEO, and assembly from Earth utilizing a single-strand tether and then multiple-strand tethers connecting the top of the tower to a GEO base asteroid counterbalance (fig. 21). The great length involved, ≈36,000 km, will require a system for materials processing, fabrication, and assembly that is as autonomous as possible.

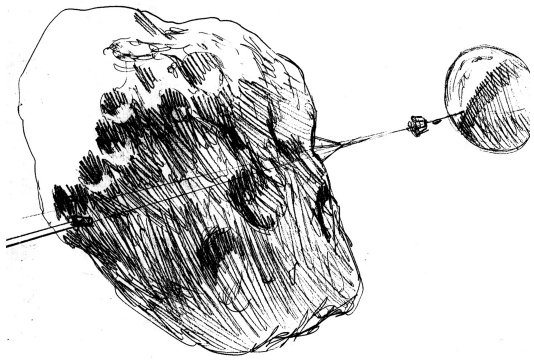


Figure 21. Asteroid attached to the space elevator beyond GEO to counterbalance the system.[5]

3.5.4 Lunar Infrastructure Elements

Developments at the Moon could have an important role to play in the overall plan to develop and demonstrate the technology for a space elevator. As described in 3.2.3 Lunar Space Elevator Concepts, materials are available today to extend a tether connection from the surface of the Moon to the L1 or L2 points in space on the near or far side, respectively. These systems could prove the technology required for construction of the space segment of the elevator before it is done on Earth. If development of lunar resources proves to be profitable for overall space development, then such resources may be useful for development of the elevator at GEO as well. In general, in-space transportation systems that are developed to move payloads from LEO to GEO will likely have the ability to go all the way to the Moon.

3.5.5 Space Resources

Development of space resources for materials and propellants will likely play an important role in overall space development as well as support development of the space elevator. As described in section 3.5.3 on robotics, these resource-mining systems will need to be as autonomous as possible, requiring limited human intervention (fig. 22).

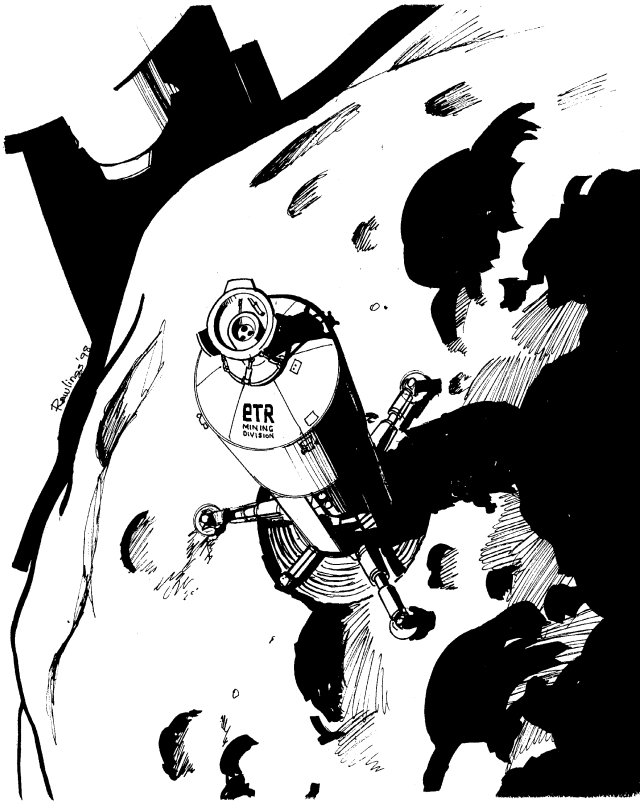


Figure 22. Asteroid materials mining.[15]

Of particular interest is the concept for utilizing an asteroid as a counterweight for the space elevator and mining its resources to produce some of its construction materials. Although this is only one of several possible approaches, it is intriguing because it requires capturing and moving an asteroid into GEO. Having the ability to track, capture, and manipulate the orbits of near-Earth asteroids is viewed by many as an important technical achievement that could prevent future large impacts on Earth.

3.5.6 Earth-Based Applications of Space Infrastructure Technology

Space exploration in general has produced many benefits on Earth that have advanced our health and standard of living. The development of space infrastructures as described in this section will certainly continue these technology advances. Of particular interest are a few of the workshop participants' ideas on what could happen, but may not, unless these space infrastructure-related technologies are developed:

- Highly reusable aerospace vehicles could provide same-day delivery and return of people and payloads around the world and into space to expand travel, tourism, and package delivery markets.

- Robust LEO to GEO transportation systems would permit human interaction in the servicing and development of large GEO platforms for a variety of industries.

- Servicing systems in space would permit lower cost satellite systems that can be refueled, upgraded, and repaired as needed.

- Space business park developments could lead to many new space industry developments for travel, tourism, entertainment, sports, film production, medical facilities, and materials development.

- Space-based power systems could provide clean power for developing countries, help resolve environmental issues surrounding the use of nuclear and fossil fuels, preserve fossil fuels for future plastic materials production, and reduce dependence on nuclear systems with related military applications.

- Reusable transportation systems from LEO to GEO could enable a new market for travel, tourism, and package delivery services beyond LEO out to lunar orbit (fig. 23).

- Autonomous inspection maintenance and repair systems could enable efficient repairs to ground utility and transportation systems and safer operations in hazardous conditions.

- Heavy-lift airships could enable logging from remote areas, high-rise construction, and lifting entire houses from manufacturing plants to residential development sites.

- Reusable space transfer vehicles would make it possible to remove orbital debris before they become a hazard to operational satellites.

- Overall LEO to GEO development would set in place a space infrastructure that could identify and realistically deal with any potential threat to Earth from large asteroids.

The interesting thing about the space elevator concept and space development in general is that the opportunity is here to chart a course for expansion that is no longer limited to the physical constraints of Earth resources. Through development of these technologies and infrastructures there will be many new benefits, products, and services that cannot possibly be envisioned at this time from an Earth perspective.

Figure 23. "Blue Moon tours"[15] is a concept for what space transportation out to the Moon and back could be like as part of a future space development infrastructure.

4. ISSUES

Major issues related to the space elevator concept tended to focus on either environmental or safety concerns. The environmental issues dealt primarily with the effects the natural environment on Earth and in space would have on the space elevator system. Some of these concerns led to safety issues for people traveling on the elevator as well as for others on Earth and in space in the event of a catastrophic failure.

4.1 Environmental Issues

In this section, environmental issues will be addressed by examining the Earth's environmental effects on the ground segment, the tower, and the space environmental effects on the space segment of the space elevator. Potential debris impacts and collisions in space are covered primarily as part of the safety issues in section 4.2.

4.1.1 Equatorial Ocean Platform

The baseline concept for the space elevator, illustrated on the cover and in figure 2, is located at the equator on an ocean platform. Initial analysis made the ocean platform attractive for both safety, transportation, and political related reasons. Land locations on islands or mountaintops along the equator are also possible.

The ocean platform provides one of the most remote locations possible for space elevator construction. This is desirable, especially for the first elevator, in the event of catastrophic failure. As described in earlier sections, the center of mass for the entire space segment of the space elevator would be located at a geostationary orbit directly over one point on the Earth's equator. In addition, the worst-case weather conditions at the equator are milder than anywhere else on Earth. This makes the equatorial location important from both a construction and stability standpoint.

The location off land is not necessarily detrimental to construction and operational access. If the base is developed as a major port for shipping and air transportation, then it can develop as a city island (fig. 24). In addition, if the base can be constructed as a floating platform and not be anchored or structurally supported from the ocean floor, then the entire structure would be mobile, such that adjustments in its final location might be possible.

A system of this scale will have both international appeal and international issues to be resolved. For that reason, its location in international waters may be an advantage for the space elevator developers by providing freedom from the many additional constraints and safety concerns that might otherwise be imposed by governmental bodies on land.

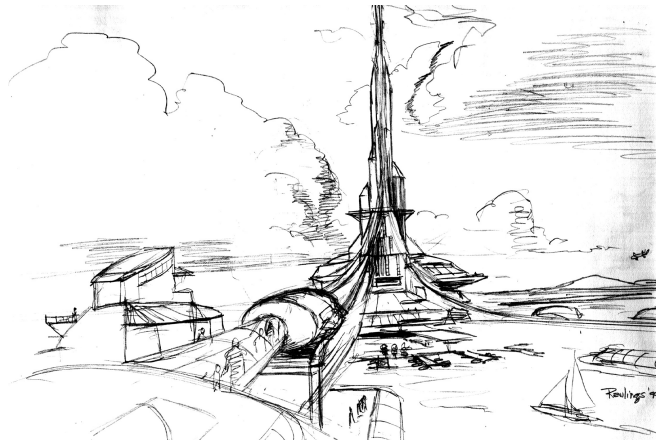


Figure 24. Concept for an ocean platform city for the base of a space elevator.[5]

4.1.2 Ocean Environmental Issues

Ocean currents at the equator move from east to west except near the surface where there is an equatorial counter current that moves from west to east. Water temperatures from 24–28 °C (75–82 °F) are typical with cold water up-wells along western coastlines near 20 °C (68 °F) periodically. Precipitation is greater than evaporation at the equatorial region, making the ocean less salty at the equator than at higher and lower latitudes.[13] Ocean depth along the equator varies to a maximum depth <8 km.[21]

4.1.3 Atmospheric Conditions

Wind conditions in the equatorial regions are calm, varying from near 0 to 16 km/hr year round. Higher wind speeds in the jet stream are <54 km/hr, and have minimal impact due to the low air pressure at higher altitudes. At altitudes of the highest stratospheric balloons, 35–45 km, the wind speed generally does not exceed 180 km/hr. At 25-km altitude the wind speed is <72 km/hr. Lower altitudes have lower wind speeds and higher altitudes have less air pressure, which results in a maximum dynamic pressure at ≈10 km in altitude.[22]

Of particular interest is that hurricanes are not possible at the equator. The rotation of the Earth causes all winds in hurricanes, tornados, and cyclones to rotate counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. At the equator the rotation can occur in either direction, but cannot sustain the high concentrations of angular momentum required for the formation of destructive windstorms.[13]

Rainfall can vary widely from 0.04 to 7.3 m per year, depending on the location along the equator. This has produced some of the most arid lands and tropical rain forests in the world in the equatorial regions.[13]

4.1.4 Gravitational Field

The most stable gravitational location for the construction of a space elevator is in the Indian Ocean at 70° E., which is south of India near the Maldives Islands. Second to that is a site in the eastern Pacific at 104° W. near the Galapagos Islands. Any location along the equator could be feasible, although some advantage might be found for the first elevator construction at one of these sites.[22]

On the island of Gan in the Maldives, the average low temperature is ≈24 °C (75 °F) and the average high temperature about 35 °C (95 °F) year round. Average relative humidity is ≈81 percent, and the annual precipitation is ≈2.4 m (95.8 in.). On the Galapagos Islands, the temperature range is 24 °C (75 °F) to 29 °C (85 °F). Upper elevations receive more moisture from mist than rainfall and the lower elevations are more arid.[22]

In general, wind and weather conditions in the equatorial regions are very mild, although it was noted that little is understood about wind gusts in the tropics to be able to identify any specific issues. Icing at altitudes in the 4- to 5-km range could occur even at the equator, so a tower extending through that part of the atmosphere would need to address this potential problem in the design of the structure, rails, and vehicles passing through at that level.

4.1.5 Space Environments

Space environmental effects on materials can be broken into distinct areas where different effects are more prominent: LEO, where atomic oxygen (AO), space debris, plasma, and ultraviolet (UV) and vacuum UV radiation effects are most prominent; and GEO, where particulate radiation, UV and vacuum UV radiation, and meteoroid effects are most prominent.

4.1.6 Low-Earth Orbit (200- to 900-km Altitude)

4.1.6.1 Atomic oxygen. Atomic oxygen in the 200- to 900-km altitude can have significant impact on spacecraft at orbital velocities. It will erode organic films and polymeric materials, oxidize metals, and can have a negative effect on the materials' thermal optical properties, conductivity, reflectivity, vacuum sealing capability, and strength. It is anticipated that the AO will erode the surface of exposed carbon materials like the future carbon nanotube structure proposed for the space elevator. On a more positive note, the natural erosion from AO can build up a protective oxide layer on some metals. So, creating a total system that includes a type of sacrificial or protective layer is conceivable. It is also noteworthy that the elevator structure is not traveling at orbital velocities since its rotation is fixed with the rotation of the Earth. This will decrease the AO effects on the space elevator structure.[23]

4.1.6.2 Space debris. Space debris is a concern for space elevator systems as well as all space systems in general. Small debris only millimeters in diameter can sever tethers, damage shielding, and potentially puncture pressure vessels, leading to catastrophic rupturing. Secondary ejecta from the initial impact can potentially cause widespread damage and produce additional hazards for other spacecraft. These issues will be dealt with in more detail in 4.2 Safety Issues.

4.1.6.3 Ionospheric plasma. Ionospheric plasma effects on materials include material erosion, changes in optical properties, arcing of thin coatings, and pitting of material leading to sputtering. Electron collection of highly positive surfaces can alter floating potential and increase parasitic current flow in the system. These energetic particles can cause damage in materials through a variety of mechanisms. For crystalline materials, elements of the crystal lattice can be displaced. This is a big problem in semiconductors and optical fibers. A charge can be deposited in a material and cause a chemical change.[23]

4.1.6.4 Ultraviolet radiation. Ultraviolet radiation will darken many materials causing changes to the optical properties of polymer materials and thermal control coatings, and pitting of anodized aluminum will occur over long-term exposure. In general, all metals require coatings with highly emissive material to prevent overheating, and the coefficient of thermal expansion of the various materials should be similar to eliminate stresses.[23]

4.1.7 Geosynchronous Orbit

4.1.7.1 Charged particles. Charged-particle effects on materials will tend to darken polymer coatings, changing their optical properties, and causing them to become brittle. Metals can become more hardened, affecting their electrical and thermal conductivity. Ceramic materials become darkened. Spacecraft charging caused by low-energy electrons produces differential charging, causing dielectric breakdown on materials. Surface coatings need to be static dissipative to prevent high charge differential.[23]

4.1.7.2 Solar ultraviolet. Solar UV tends to neutralize charge buildup. Because parts of the spacecraft are shadowed, the photoelectric effect tends to produce differential charging. Molecular contamination from the spacecraft under action by UV darkens external surfaces, degrading its thermal optical properties. Even silicone exposed to UV and AO tends to darken, degrading its thermal and optical properties.[23]

4.1.7.3 Meteroids. Meteoroids are a concern for space elevator systems as well as all other space systems. Whereas the space debris environment can be cleaned up over time, there is no control over incoming meteoroids from space. This issue will also be dealt with in more detail in section 4.2.

In general, the space environmental effect on materials is important to the design of the space elevator system. Past flight experiments provide a good database of space environmental effects on materials, and new materials being developed will always require testing to determine material survivability in the space environment.

4.1.8 Energy From the Space Environment

Several ideas for generating energy from the space environment to help lift, stabilize, and operate the space elevator were suggested. They include collection of ionospheric currents to produce power, use of controlled tether currents to drive against the geomagnetic field (especially the lower altitude portion), and the feasibility of creating a short circuit between the electron and proton belts to generate energy. These ideas were not studied in depth, but were identified as areas needing further research.

4.2 Safety Issues

The single greatest safety concern identified centered on the hazards caused by potential collisions between the elevator structure and other objects in orbit. This included orbital debris, active spacecraft, and meteoroids. Orbital debris includes everything from paint chips to dead satellites, which are a threat to all active spacecraft today. Cleanup of orbital debris was identified as a high priority that needed to be done to protect all future spacecraft. Active spacecraft were also considered a threat to the space elevator but it was noted that future systems could include collision avoidance navigation systems. Meteoroids from space were perhaps the only natural debris hazard that will impact the maintainability of a space elevator structure. Impacts that could cause significant damage were found to be remote, but possible.

4.2.1 Space Debris Analysis

The U.S. Air Force tracks ≈8,700 objects 10 cm in diameter or larger that are orbiting the Earth. Of those objects, only 300 to 400 are operational spacecraft. The remaining debris is due to nonfunctioning spacecraft, spacecraft breakups, one known collision, and a few unknown sources. Figure 25 provides the relative distribution of known objects in Earth orbit from LEO to beyond GEO at 50,000-km altitude.

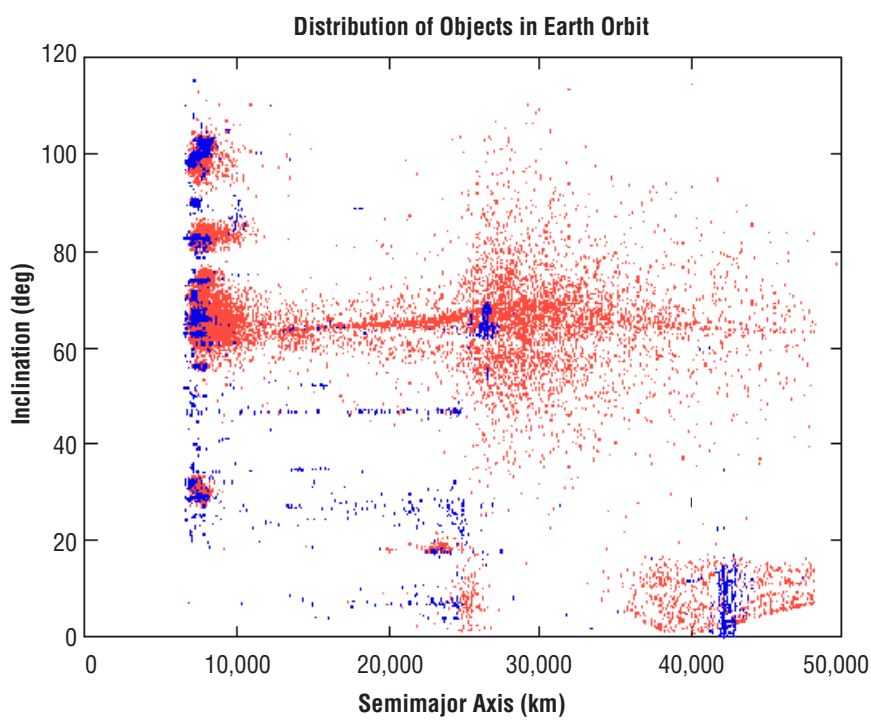


Figure 25. Tracked space satellites and debris distribution.[24]

Small debris materials <1 mm in diameter are numerous and can cause erosion of spacecraft surfaces. Space junk larger than 10 cm in diameter can be tracked by ground radar systems for collision avoidance purposes, and could eventually be captured and removed from Earth orbit. The real problem is with debris and incoming meteoroids in the 1 mm to 10 cm size. They are difficult to track with current technology and can cause significant damage to spacecraft systems.

Space debris and meteoroids 1 mm to 10 cm in diameter are thought to be many times greater in number than the known tracked objects. For example, figure 26 examines the impact incidents for an elevator that is built out in both directions from GEO to a full-balanced length at 144,000 km. A 144,000-km tether only 1 mm in diameter yields an exposed surface area of 14,400 m^2. For particles ≈1 mm in diameter, collisions with the space elevator would occur at a rate of approximately three impacts per day. Larger sized objects at 10 cm in diameter would impact the elevator at less than one per year. This is still significant since a larger sized structure is likely. For example, an exposed area of 1 m along the entire length would increase the number of impacts for 10-cm-sized objects to between 100 and 1,000 per year. This indicates that the design of the space elevator structure will have to consider many options for both withstanding impacts, avoiding potential collisions, and making repairs when impacts occur.

General cleanup of space debris from Earth orbit was identified as a high priority for the space elevator and for current and future spacecraft. The infrastructure needed for space development in general, as identified in section 3.5, would create systems that could be used to track and collect orbital debris as part of an ongoing mission to keep the orbital environment safe for everyone.

4.2.2 Space Elevator Collision Avoidance

The first space elevator will probably not be built until after the current generation of space assets have been used up. Next-generation space systems could be designed with the space elevator structure in mind and include automated collision avoidance systems for both satellites and the space elevator. This will be critical because all objects orbiting the Earth cross the equator twice per orbit and have the potential of colliding with a space elevator structure. Figure 27 illustrates the problem. For example, a satellite in a circular orbit at 10,000-km altitude has a 6-hr period and will cross the equator every 3 hr.

Human-rated spacecraft like the Space Shuttle orbit the Earth at much lower altitudes with a 90-min period, crossing the equator once every 45 min. This equates to ≈32 equatorial crossings per day, or 11,680 crossings per year. The good news

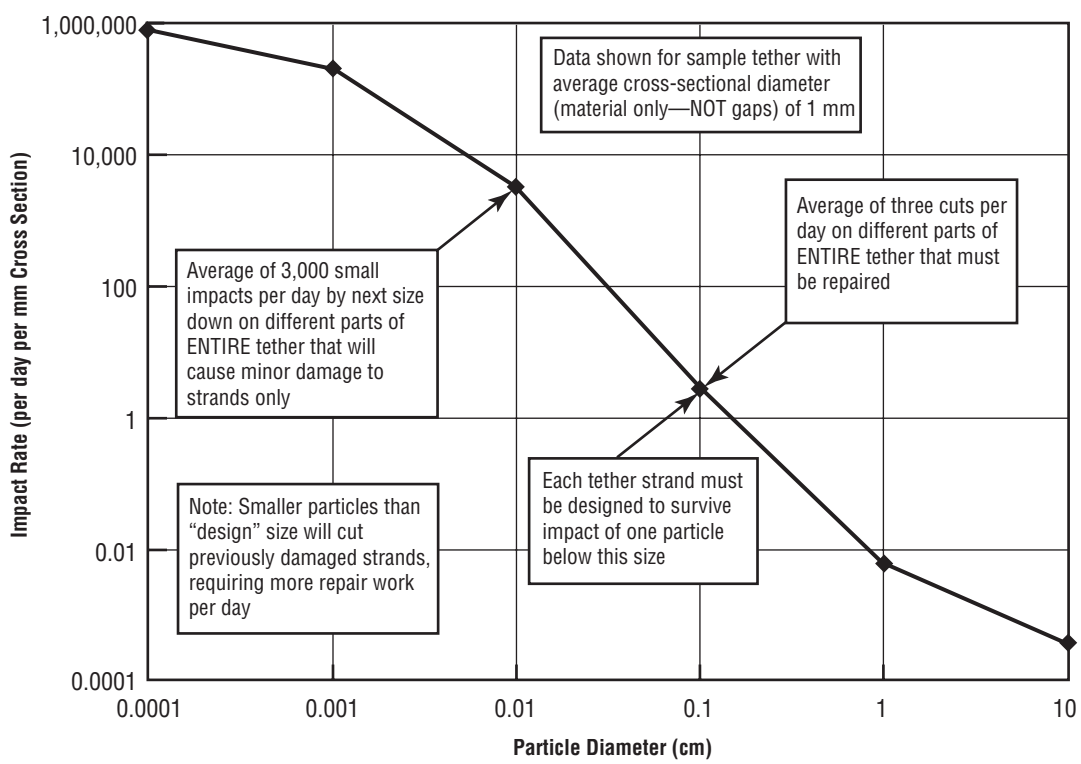


Figure 26. Sizing tether strands based on repairs per day.[25]

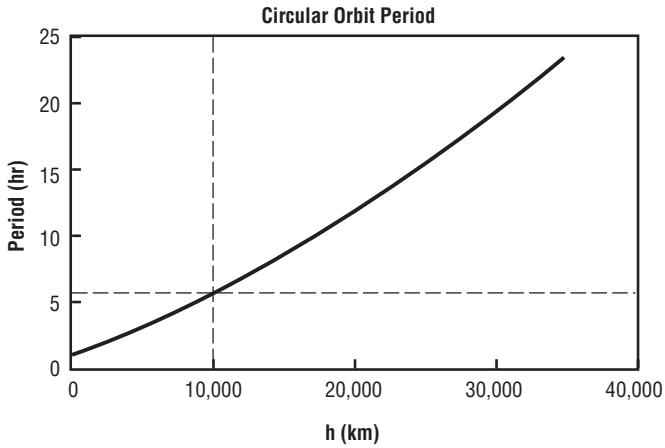


Figure 27. Orbital periods.[26]

is that the orbital trajectories can be determined in advanced. Proper trajectory adjustments made at regular intervals or as part of the normal reboost of LEO spacecraft could be made to avoid the space elevator structure.

Many new satellite constellations are under development for the mobile telephone industry. With the growth of communications, remote sensing, Global Positioning Systems (GPS's), and other Earth observation systems, it is apparent that the orbits from LEO to GEO will be populated by perhaps thousands of operational spacecraft by the time the technology is mature enough to build a space elevator. This congestion could improve the feasibility of space elevator structures by forcing, in advance, the cleanup of all orbits and the development of automated collision avoidance technology for all satellite systems.

Another issue to consider is the effect a space elevator will have on other major space infrastructure developments like a space station, which are not so easily moved. Figure 28 indicates that a space station similar in size to the *ISS* would make collision avoidance maneuvers at irregular intervals averaging maybe once per year to once per month, depending on the clearance range desired. It was determined that these collision avoidance maneuvers could probably be done efficiently as part of the regular station reboost operations which normally occur several times per year. It appears important then that when collision avoidance systems are incorporated on both the space elevator and the spacecraft, such systems should be very accurate to permit low collision avoidance ranges. In other words, technology should be developed to allow clear or keepout ranges to be measured in meters, not kilometers, and automation will be needed to track and implement the thousands of commands per year.

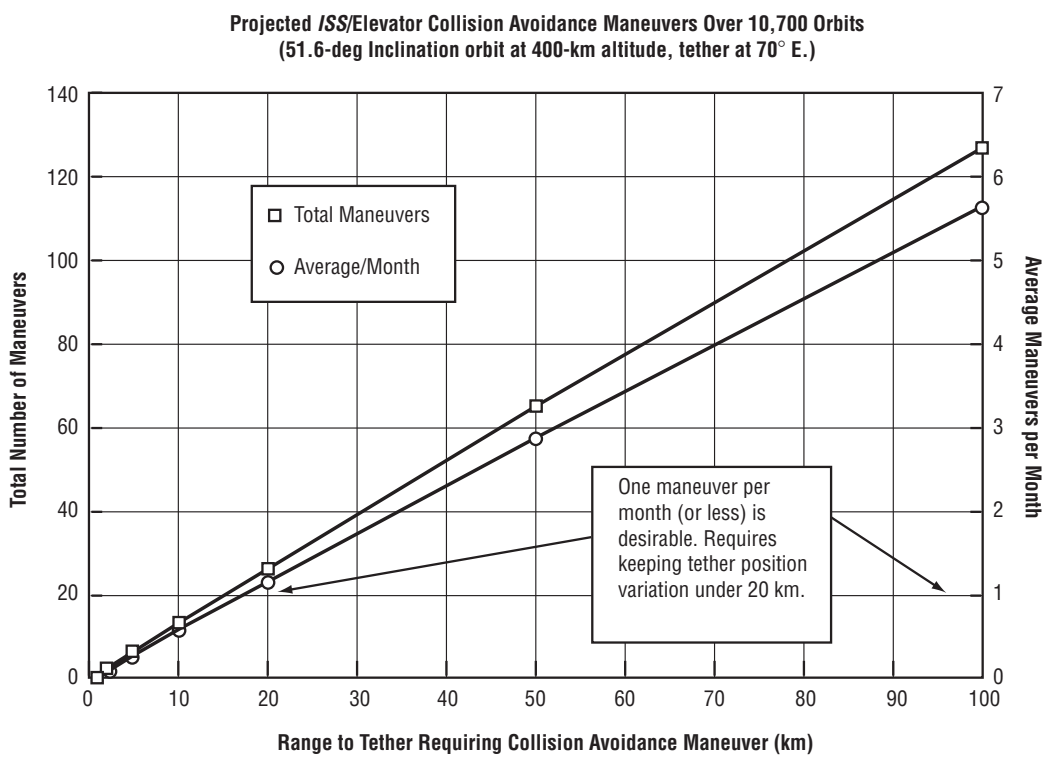


Figure 28. Maneuvers required by a space station (using *ISS* as an example) to avoid a fixed space elevator structure in LEO.[24]

Various options have been envisioned for doing collision avoidance on the elevator structure including swinging the entire structure and actively bending or vibrating the structure. Figure 29 illustrates the kind of flexibility a semirigid structure 36,000 km in length could have. Such control would be an active system capable of moving to any point on the elevator structure.

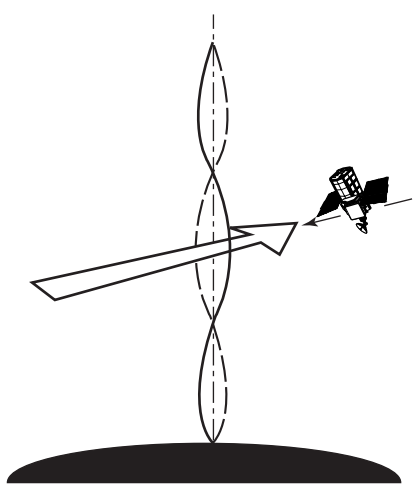


Figure 29. Bending the space elevator for collision avoidance.[24]

This is the vision behind the thruster modules illustrated in figure 30. At any given time, a portion of the elevator structure is moved laterally many hundreds of meters, perhaps kilometers, to implement the collision avoidance maneuver. The operation of the elevator is not affected since a kilometer move laterally has little effect over the 36,000-km length of the total structure.

4.2.3 Catastrophic Failure Modes

Catastrophic failure or the complete severing of the space elevator structure is the ultimate disaster that must be considered in the design of a safe system. Such failure could occur through impacts from space objects, excessive vibration of the entire structure, or unanticipated structural stresses from temperature variations or orbital dynamics, causing material failures.

Objects released from the space elevator below ≈25,000-km altitude will fall back to Earth, objects released between 25,000 and 47,000 km will enter an Earth orbit, and objects released beyond 47,000-km altitude will escape Earth orbit. If

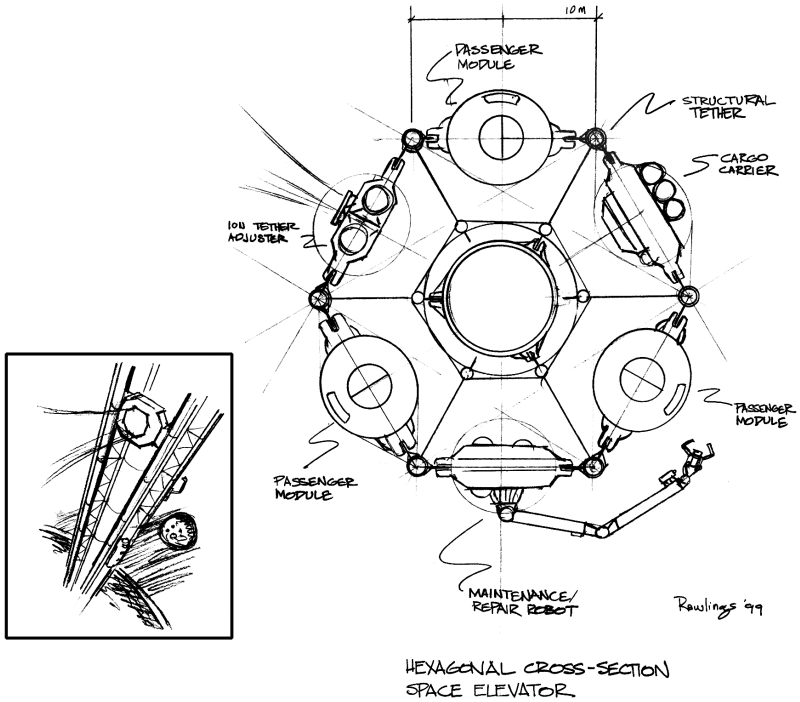


Figure 30. Space elevator cross section.[5] Conceptual cross section of a space elevator showing high-speed passenger modules, cargo carrier, maintenance and repair robot, and a lateral propulsion module for collision avoidance control at any point on the elevator structure. Note also that the cross section of the entire structure is large enough that a direct hit from a large upper stage would not break all of the structural cables. This kind of basic design thinking will need to be put into the space elevator to ensure that catastrophic failure does not occur.

the structure is completely severed, an approximate 3- to 4-km/sec ΔV capability is needed to ensure either remaining in orbit or having a soft reentry. Given these general parameters, several options are apparent for vehicles traveling on the elevator and the total elevator systems.

Passenger vehicles traveling the elevator could require several backup modes. In the event of some system failure where the module escapes or is ejected from the space elevator track, a safe return capability could be as follows. For low altitudes in the Earth's atmosphere, a parachute deployment system with inflatable landing surfaces could be considered. Above the Earth's atmosphere, a rocket propulsion system providing the boost needed to reach a safe orbit would be the desired approach.

The space elevator structure would likely take a different approach depending on where the break occurs. If the lower section is a self-supporting tower rising through the atmosphere, then a release point would be provided between the tower and the space segment of the elevator. A break at this point would cause the remaining space segment to rise. A break between the top of the tower and 25,000-km altitude would cause the lower section to fall back to Earth and the upper section to rise into a higher orbit. Hence, the problem area to be dealt with is the lower space segment of the elevator between the top of the tower and 25,000-km altitude.

The most desirable approach would be to have propulsion systems on the elevator capable of moving the space segment of the elevator <25,000-km altitude into a safe orbit for repair and reassembly. Second to that would be a capability for controlled reentry into a remote ocean region. Propulsion systems have already been identified as a need for collision avoidance; so, robustness of the total system should include control of the lower section in the event of such a catastrophy.

In summary, it appears important that a system needs to be put in place to track and clear out all orbital debris. This would be good for the future space elevator as well as all other current and future space systems. The design of the space elevator should expect regular impacts from meteoroids that will cause surface erosion and sever some structural strands. A plan providing for ongoing repair and maintenance of the entire structure should be part of the design. Individual strands should be designed to survive below a "design" particle size, probably 1 mm in diameter. Large impacts should be considered too, such that the structure is large enough in diameter to avoid a total break. Collision avoidance systems will be needed for both the elevator and all other spacecraft. This technology for future systems should be very accurate in the detection of objects <10 cm, be capable of reduced clear zones measured in meters, and should be automated to the greatest extent possible. Finally, propulsion systems that can move lower segments of the space elevator should be included in the design in the event of a complete break in the elevator structure.

5. CONCLUSIONS AND RECOMMENDATIONS

The massive size and complexity of the space elevator concept is often cited as making such a system impossible to conceive except in the realm of science fiction. More detailed analysis of the system indicates that it is indeed very complex, but it is comparable to other Earth-based infrastructures that have been built over many years. For example, the mass of the PBO tower referenced in 3.3 Compression Structures connected to a GEO tether has a mass greater than a recent Norwegian North Sea oil-drilling platform, 1 million tons, but is less massive than the 5 million tons of the Great Pyramid of Giza. And even the length of the space elevator, ≈36,000 km from Earth to GEO, is short in comparison to our interstate highway system that extends some 100,000 km, with a mass of several thousand million tons. Other great infrastructure accomplishments similar in scale would include the Great Wall of China, Panama Canal, and our utility systems for communications, electricity, gas, water, and sewage. Similar efforts would seem to make a space elevator conceivable.[6] The following section provides the groups' thoughts on the pros for building a space elevator, the cons against building a space elevator, some concerns and possible solutions, and recommendations for future consideration.

5.1 Pros for Building Space Elevators

Many benefits were identified that supported the pursuit of space elevator technology, most of which centered on the potential for low-cost mass transportation capabilities to space. Those ideas were as follows:

- The space elevator is one of very few concepts that may allow Earth to orbit launch costs less than $10/kg.
- Lowering launch costs to $10/kg and less will open up near-Earth space to miners, explorers, settlers, and adventurers, which will give us a frontier society once again. This will alleviate any perception of over-crowding and scarcity of resources.
- The technology for developing a space elevator appears to be within reach during the next century or perhaps next few decades.
- A surface to GEO space elevator would be good for placing satellites into GEO and allows lower acceleration into orbit for fragile cargo. It is a potential mass transportation system to space equivalent to the highways, railroads, pipelines, and utility grids on Earth.

- A space elevator can allow the construction of massive solar-powered systems in orbit and help carry the power down to Earth. This could alleviate the problems of large-scale power production in the biosphere, end strip-mining for coal, reduce power plant emissions, reduce greenhouse gas production, lower radiation levels, and perhaps have a positive impact on global warming concerns.

- A space elevator extending beyond GEO (toward the ballast mass) could provide escape velocity for propellant-free transfer orbits to the Moon, Mars, and all the way out to Mercury and Saturn.

- A surface to GEO space elevator may be the only way to feasibly build large space-based cities and colonies for continued expansion into space. GEO can support massive space cities with minimal collision concerns with other spacecraft.

- The elevator concept could be more environmentally friendly than burning rocket fuel in the atmosphere necessary to do the same tonnage.

- A GEO complex supported by a space elevator could be the site for manufacturing and metal fabrication in orbit, reducing the amount of pollution on Earth.

- Using extraterrestrial materials from nearby asteroids not only utilizes their resources but develops the technology to rid space of potential asteroid strikes on Earth.

- A side benefit of materials research for the space elevator would be a massive reduction in fuel use here on Earth from lighter weight structures in automobiles, trains, ships, and planes.

- The space elevator is like a bridge that can support an unlimited amount of mass delivery between Earth and GEO.

- Space elevators for the Earth, Moon, and Mars could create a complete inner solar system transportation infrastructure with minimal use of rocket systems.

- The space elevator could revolutionize space flight and space development. It could be the key to moving polluting industries and power production into space and ending pollution of the biosphere.

5.2 Cons Against Building Space Elevators

There are many questions and problems to be resolved before space elevators can be considered feasible. Some of these problems are as follows:

- Financial tradeoffs (initial investment cost versus payback) and ultimate launch cost ($/kg) have not been addressed—there may not be any real cost benefit.

- Assuming that the purpose of the elevator is to deliver mass to GEO, one must ask what the cost of this delivery may be using other exotic techniques that may come to maturity in the next 50 yr.

- If the travel time on the elevator is over 24 hr, this may prove to be unacceptable to the paying public. Long tether rides will require vehicles the size of railroad cars that include restroom facilities, cafeterias, entertainment, and even sleeping quarters.

- Using simpler surface to sub-LEO space towers could offset benefits of a surface to GEO space elevator for the telecommunications industry. The tall towers could make the large GEO communications satellites obsolete.

- An equatorial orbit, especially the GEO, is a poor orbit from which to go to the Moon or Mars, or to do almost any escape mission. The escape direction is almost always not in the equatorial plane. Large plane changes would still be required.

- A catastrophic failure of a space elevator could produce massive political, legal, financial (lawsuits), and ecological disasters with massive loss of human life.

- Eighty percent of the benefit will be gotten from the first 10 percent of the project (tower or tether) in improving the payload fraction of an SSTO from 1–2 to a 10-percent range, at which point airplane-like operations in the few dollars per kilogram range should be possible.

- If structural materials good enough for a space elevator are available, an SSTO with a healthy payload fraction and safety margins, which will operate with airplane-like operating costs, can also be built.

- There are numerous political issues that will need to be addressed in order for a space elevator to be constructed.

- Any project planning with more than a 20-yr time horizon is a waste of time because predictions cannot be made as to what will happen to technology in that timeframe.

- The space elevator seems too far in the future relative to the space infrastructure that could develop from more near-term propulsion technology. Also, even if it were to be possible to build today, it is not clear that it can drastically reduce the cost of delivering mass into orbit.

5.3 Concerns and Possible Solutions

There are many things that need to be done before a space elevator can actually be considered a feasible approach for accessing the space frontier. The following concerns were collected along with an explanation of what could be done to help determine feasibility or alternative approaches:

- An operations assessment needs to be performed before the space elevator can seriously be considered: power requirements, collisions, maneuverable tethers, initial assembly, maintenance concepts, contingency plans for damage and breaks, and simultaneous use by many users.

- All the technical problems are important; however, the real problem is how to fund it. It must be shown that it is a commercially viable program. Thus, there has to be payback to commercial partners that is in a timeframe of interest to them. To achieve this payback, the facility cannot just be used for launching spacecraft into orbit or to the stars. It would need to have multiple commercial applications such as communications, entertainment, or recreation. It should be built in stages to allow for growth into a true space elevator; each stage would have to pay for itself.

- Satellites and space stations in LEO and MEO can coexist with a space elevator if the position of the elevator is well known and broadcast (like GPS) to the spacecraft operators so that they can redirect the satellite when necessary. Minimal orbital adjustments every year or two (random intervals) would be required to avoid collision with a space elevator in most cases.

- The space elevator makes a lot of sense if materials with characteristics like carbon nanotubes become available for long tethers in ton quantities. Short of carbon nanotube performance, the space elevator is far too massive.

- An analysis of an Earth surface to GEO elevator was done in 1988 using T1500 graphite fibers (1,500-ksi fibers). It was found that the concept was not economically viable as a commercial system when amortization of the investment was included in the cost model and based on any possible near-term traffic model. The payload mass flow required to make this concept work economically is so far beyond where we are today that there is just no way to a full-up Earth surface to GEO elevator without a few intermediate steps.[27]

- Good space development policy is perhaps the most important determinate as to whether space development, and eventually space elevator development, will come to fruition. A number of barriers must be overcome before progress can be made.

5.4 Recommendations

The space elevator is not a near-term project but a potential project for the latter part of the 21st century. Sections 5.4.1 through 5.4.6 cover activities that were identified for the near term that would help determine the feasibility of space elevators and would lead down a technology path for their development.

5.4.1 Space Development

- Promote a national commitment to space development. This does not necessarily mean putting a lot of public money into space infrastructure development. It does mean that all branches of government have a natural role to help economic expansion in space in the same way that they have helped with economic expansion from the east to west coast.

- Initiate studies to do detailed computational modeling for the space elevator concepts that include realistic structural, mechanical, orbital, atmospheric, and operational aspects of the system. Include some detailed life cycle cost analyses to determine range of dollars per kilogram for user launch costs.

- Analyze cost-effectiveness of space elevators as compared to other projected means for placing personnel and equipment in the space environment for the timeframe under consideration.

- Analyze catastrophic failure modes to determine the best methods to salvage and reconnect the structure to prevent deorbiting and collapse of the entire system.

- Demonstrate critical technologies prior to space elevator development including tether systems in space, tall towers on Earth, and electromagnetic propulsion systems. Integrate the technology roadmap shown in figure 1 into national technology programs to ensure progress is made toward Earth to GEO space elevator developments in the latter part of the 21st century.

- Promote an international dialog on space elevators to ensure long-term acceptance and support for the concept. Even though it is very futuristic, it is good to begin documenting and working the technology now so the concept will have sufficient time to be considered internationally.

- Establish a space tower foundation that over time could explore all the options for space elevator construction,

fund technology demonstrations of the various components, and help guide the technology developments needed for its construction and safe operation.

5.4.2 Materials

- Develop advanced high-strength materials like the graphite, alumina, and quartz whiskers that exhibit laboratory strengths over 20 GPa.

- Continue development of the carbon nanotube materials that exhibit strengths 100 times stronger than steel in excess of 62.5 GPa that may be required for space elevator construction. Introduce these new lightweight, high-strength materials to the commercial, space, and military markets for new and improved product developments.

- Continue development of carbon nanotube technology even if the space elevator itself is questionable. Lightweight, high-strength materials could resolve many other terrestrial and space development problems.

5.4.3 Tethers

- Continue development of space tether technologies for space transportation systems to gain experience in the deployment and control of long structures. Utilize higher strength materials as they become available. Continue analysis and plan for demonstration of momentum exchange and LEO space elevator facilities for low-cost, in-space transfer to GEO.

- Continue development and demonstration of tethers in the space environment at progressively higher altitudes and longer lengths. The LEO to GEO elevator needs careful simulation. It is not clear that this is dynamically stable in operation due to coriolis forces.

- Initiate studies to determine the potential current collection and power generation from the plasma environment. Calculate the electromotive propulsion using tether currents against the geomagnetic field for stabilization.

5.4.4 Towers

- Introduce lightweight composite structural materials to the general construction industry for the development of tall tower and building construction systems. Foster the development of multikilometer-height towers for commercial applications; i.e., communications, science observatories, building construction, and launch platforms.

- Evaluate markets for tall tower services including communications, science platforms, launch assist, and entertainment. If a tower market (e.g., communication) appears viable, undertake prototype construction for that purpose—ideally, with partial private sector support.

5.4.5 Electromagnetic Propulsion

- Develop high-speed electromagnetic propulsion for mass transportation systems, launch assist systems, and high-velocity launch rails. Integrate electromagnetic propulsion devices into conventional construction industry systems; i.e., doors, elevators, conveyors, etc.

5.4.6 Space Infrastructure

- Do trade studies to determine the optimum split in ΔV between an SSTO, a tower to start from, and a tether in orbit to land at, to determine the overall optimum in lowering total capital cost and operations cost. The SSTO by itself is hard, the space elevator by itself is hard; a combination of both may be better than either one alone.

- Initiate policies that require launch and payload companies to clean up anything they leave behind to drive incentives for debris removal systems. Fund cleanup of other debris from fees and licenses for use of orbital slots.

- Develop transportation, utility, and facility infrastructures to support space construction and industrial development. Key components include highly reusable space launch systems, reusable in-space transportation, and space facility support from LEO to GEO.

This review of the space elevator concept has determined that it is indeed a very large and complex project but is not unlike many of the large infrastructures that have already been developed for transportation and utility systems over many years. Even though technology for space elevator construction may be a number of decades away, it does appear that there are productive actions that can be pursued now that could lead to its eventual development. In addition, pursuit of these recommendations and the concepts envisioned in this publication, could provide significant intermediate benefits for the economic development of space and overall technology advancement in general.

APPENDIX A—WORKSHOP PARTICIPANTS AND CONTRIBUTORS

A.1 Workshop Participants

Joe Carroll,
Tether Applications

Robert Cassanova,
NASA Institute for Advanced Concepts

John Cole,
NASA Marshall Space Flight Center

Dani Eder,
Boeing Company

Robert Frisbee,
Jet Propulsion Laboratory

Les Johnson,
NASA Marshall Space Flight Center

Scott Johnson,
USAF Academy

Ronnie Lajoie,
Boeing Company

Geoffrey Landis,
NASA Glenn Research Center

Enrico Lorenzini,
Smithsonian Astrophysical Observatory

John Mankins,
NASA Headquarters

Brice Marsh,
CSC

Daniel O'Neil,
NASA Marshall Space Flight Center

Jerome Pearson,
Star Technology and Research, Inc.

Paul Penzo,
Jet Propulsion Laboratory

Pat Rawlings,
Science Applications International Corporation

Eric Smith,
Global Hydrology and Climate Center

Frayne Smith,
Consultant

Ken Smith,
Rice University

David Smitherman,
NASA Marshall Space Flight Center

Rob Suggs,
NASA Marshall Space Flight Center

Jason Vaughn,
NASA Marshall Space Flight Center

A.2 Additional Contributors and Virtual Research Center Participants

Ivan Bekey,
Bekey Designs

Preston McGill, NASA
Marshall Space Flight Center

Eagle Sarmont,
Consultant

Robert Forward,
Tethers Unlimited, Inc.

Joe Howell, NASA
Marshall Space Flight Center

Garry Lyles, NASA
Marshall Space Flight Center

Richard Smalley,
Rice University

REFERENCES

1. Frisbee, R.H.: "Alternative Launch Concepts," Unpublished presentation, Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, NASA Marshall Space Flight Center, June 8–10, 1999.

2. *Guinness World Records 2000*, Millennium Edition, 2000 Guinness World Records Ltd., 2000.

3. Frisbee, R.H.: "Earth-to-Orbit Towers," http://sec353.jpl.nasa.gov/apc/Tethers/03.html Accessed January 27, 2000.

4. Hyde, R.A.: "Earthbreak: Earth-to-Space Transportation," *Defense Science 2003+ 4*. No. 4, August/September, pp. 78–92, 1985.

5. Rawlings, R.P.: NASA artwork by Pat Rawlings, Science Applications International Corporation, prepared during the Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, NASA Marshall Space Flight Center, June 8–10, 1999.

6. Landis, G.A.; and Cafarelli, C.: "The Tsiolkovski Tower Re-Examined," *Journal of the British Interplanetary Society,* Vol. 52, pp. 175–180, 1999.

7. Lorenzini, E.C.: "Space Elevators: Introduction to the Topic," Unpublished presentation, Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, NASA Marshall Space Flight Center, June 8–10, 1999.

8. Smalley, R.E.; and Smith, K.: "Buckytubes and Their Future," Unpublished presentation, Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, NASA Marshall Space Flight Center, June 8–10, 1999.

9. Carroll, J.: "Notes on Growing a Space Elevator," Unpublished presentation, Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, NASA Marshall Space Flight Center, June 8–10, 1999.

10. Sarmont, E.: "Affordable to the Individual Space Flight," http://www.affordablespaceflight.com Accessed January 27, 2000.

11. Sarmont, E.: "How an Earth Orbiting Tether Makes Possible an Affordable Earth-Moon Space Transportation System," SAE Technical Paper 942120, Presented at Aerotech 1994, Los Angeles, CA, October 3–6, 1994.

12. "Electrodynamic Tether Propulsion," http://std.msfc.nasa.gov/astp/tethers_electetherprop.html Accessed January 27, 2000.

13. "ProSEDS," http://std.msfc.nasa.gov/astp/proseds.html Accessed March 13, 2000.

14. Pearson, J.: "Anchored Lunar Satellites for Cislunar Transportation and Communication," *Journal of Astronautical Sciences,* Vol. 26*,* No. 1, pp. 39–62, 1979.

15. Rawlings, R.P.: NASA artwork by Pat Rawlings, Science Applications International Corporation, Prepared during the New Space Industries Workshop, NASA/CP—1998–209006.

16. Penzo, P.A.: "The Case for Mars II," *AAS, Science & Technology Series*, Vol. 62, pp. 445–465, July 1984.

17. Eder, D.: "Towers," Unpublished presentation, Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, NASA Marshall Space Flight Center, June 8–10, 1999.

18. Landis, G.A.: "Compression Structures for Earth Launch," AIAA Conference Publication AIAA–98–3737, 24th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 13–15, 1998.

19. Pearson, J.: "The Orbital Tower: A Spacecraft Launcher Using the Earth's Rotational Energy," *Acta Astronautica,* Vol. 2*,* No. 9/10, pp. 785–799, September/October 1975.

20. Smitherman, Jr., D.V.: Artwork courtesy of David Smitherman.

21. *World Book Encyclopedia*, World Book, Inc., 1993.

22. Suggs, R.M.: "Space Environments and Effects Overview," Unpublished presentation, Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, NASA Marshall Space Flight Center, June 8–10, 1999.

23. Vaughn, J.: "Space Environmental Effects on Materials," Unpublished presentation, Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, NASA Marshall Space Flight Center, June 8–10, 1999. See also "The Natural Space Environment: Effects on Spacecraft," *NASA Reference Publication 1350*, November 1994.

24. Lajoie, R.M.: "Space "Debris" and Elevator Tethers," The Boeing Company, Unpublished presentation, Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, NASA Marshall Space Flight Center, June 8–10, 1999. See also, "Meteoroids and Orbital Debris: Effects on Spacecraft," *NASA Reference Publication 1408*, August 1997.

25. Rossi, A.: "Long-Term Evolution on Earth Oribiting Debris," Paper presented at the IAU Colloquim 165, Poznan, Poland, July 1–5, 1996, Figure 3 from Web site http://apollo.cnuce.cnr.it/~rossi/publications/iau/node2.html Accessed May 1999.

26. Cole, J.: "Some Geo-Synch Tether Concerns," Unpublished presentation, Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether "Space Elevator" Concepts, NASA Marshall Space Flight Center, June 8–10, 1999.

27. Sarmont, E.: Private communication, July 7, 1999.

BIBLIOGRAPHY

Artsutanov, Y.: original is in Russian, "V kosmos na elektrovoze" "Into the Cosmos With an Electric Locomotive," *Komsomolskaya Pravda*, July 31, 1960.

Artsutanov, Y.: "Into Space Without Rockets: A New Idea for Space Launch," AFSC Foreign Technology Division Report ADA084597, Air Force Systems Command, Wright-Patterson AFB, 1969.

Birch, P.: "Orbital Ring-Systems and Jacob's Ladders—I," *Journal of British Interplanetary Society*, Vol. 35, No. 5, pp. 475–497, May 1983.

Birch, P.: "Orbital Ring-Systems and Jacob's Ladders—II," *Journal of British Interplanetary Society,* Vol. 36, pp. 115–128, 1983.

Birch, P.: "Orbital Ring-Systems and Jacob's Ladders—III," *Journal of British Interplanetary Society,* Vol. 36, pp. 231–238, 1983.

Breakwell, J.V.; and Andeen, G.B.: "A Hanging Chain in Orbit," AIAA/ASME/SAE 17th Structures, Structural Dynamics and Materials Conference Proceedings, p. 89, 1976.

Carroll, J.A.: "Tether Applications in Space Transportation," *Acta Astronautica*, Vol. 13, No. 4, pp. 165–174, 1986.

Clarke, A.C.: *Fountains of Paradise*, Harcourt Brace Jovanovich, New York, 1978.

Clarke, A.C.: "The Space Elevator: 'Thought Experiment' or Key to the Universe?" *Advanced Earth Oriented Applications of Space Technology I*, Vol. 1, pp. 39–48, 1981.

Collar, A.R.; and Flower, J.W.: "A (Relatively) Low Altitude 24-Hour Satellite," *Journal of British Interplanetary Society,* Vol. 22, pp. 442–457, 1969.

Cron, A.C.: "Applications of Tether in Space," *NASA Conference Publication 2365*, Vol. 2, pp. 5-55–5-61, Proceedings of a workshop sponsored by NASA, Washington, DC and Marshall Space Flight Center, Huntsville, AL, held in Williamsburg, VA, June 15–17, 1983.

Eder, D.: "Canonical List of Space Transport and Engineering Methods," Version 0.76, Unpublished document, August 23, 1995.

Forward, R.; and Maravec, H.P.: "High Wire Act," *Omni*, Vol 3, No. 10, pp. 44–47, July 1981.

Forward, R.L.: *Indistinguishable from Magic*, Baen Books, New York, pp. 59–89, 1995.

Frisbee, R.H.: "Earth-to-Orbit Towers," Advanced Propulsion Concepts, http://sec353.jpl.nasa.gov/apc/Tethers/03.html Accessed January 27, 2000.

Hyde, R.A.: "Earthbreak: Earth-to-Space Transportation," *Defense Science 2003+,* Vol. 4, No. 4, pp. 78–92, August/September 1985.

Isaacs, J.D.; et al.: "Satellite Elongation into a True 'Sky Hook'," *Science*, Vol. 151, pp. 682–683, February 1966.

Landis, G.A.: "Compression Structures for Earth Launch," *AIAA Conference Publication AIAA–98–3737*, 24th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 13–15, 1998.

Landis, G.A.; and Cafarelli, C.: "The Tsiolkovski Tower Reexamined," *Journal of the British Interplanetary Society,* Vol. *52*, pp. 175–180, 1999.

Lemke, E.H.: "On a Lunar Elevator," *Acta Astronautica*, Vol. 12, No. 6, pp. 385–396, June 1985.

Lorenzini, E.C.; Arnold, D.A.; Gullahorn, G.E.; and Grossi, M.D.: "Study of an Orbiting Tethered Dumbbell System Having Positive Orbital Energy," Addendum to Final Report: NASA Contract NAS8–35497, February 1985.

Lvov, V.: "Skyhook: Old Idea," *Science*, Vol. 158, pp. 946–947, 1967.

Moravec, H.: "A Non-Synchronous Orbital Skyhook," *Journal of Astronautical Sciences,* Vol. 25, No. 4, pp. 307–322, 1977.

Pearson, J.: "Achievable Space Elevators for Space Transportation and Starship Acceleration," *NASA Conference Publication 10059*, Vision–21: Space Travel for the Next Millennium, April 3–4, 1990.

Pearson, J.: "Anchored Lunar Satellites for Cislunar Transportation and Communication," *Journal of Astronautical Science*s, Vol. 26*,* No. 1, pp. 39–62, 1979.

Pearson, J.: "Konstantin Tsiolkovski and the Origin of the Space Elevator," IAF Congress Publication IAF–97–IAA.2.1.09, 48th International Astronautical Congress, Turin, Italy, October 6–10, 1997.

Pearson, J.: "The Orbital Tower: A Spacecraft Launcher Using the Earth's Rotational Energy," *Acta Astronautica*, Vol. 2, No. 9/10, pp. 785–799, September/October 1975.

Pearson, J.: "Using the Orbital Tower to Launch Earth-Escape Spacecraft Daily," IAF Congress Publication IAF–76–123, 27th International Astronautical Congress, Anaheim, CA, October 10–16, 1976.

Penzo, P.A.: "Earth Orbit Tether Transportation System," AAS Paper 87–436, AAS/AIAA Astrodynamics Conference, Kalispell, MT, August 10–13, 1987 1987.

Penzo, P.A.: "Lunar Orbit Tether Station Concept," Calspace Study, *NASA Report CR–172084*, June 1988.

Penzo, P.A.: "Tethers for Mars Space Operations," *AAS Science & Technical Series, The Case for Mars II*, Vol. 62, pp. 445–465, July 1984.

Sarmont, E.: Web site for image and technical information on a LEO space elevator concept, http://www.affordablespaceflight.com Accessed June 1999.

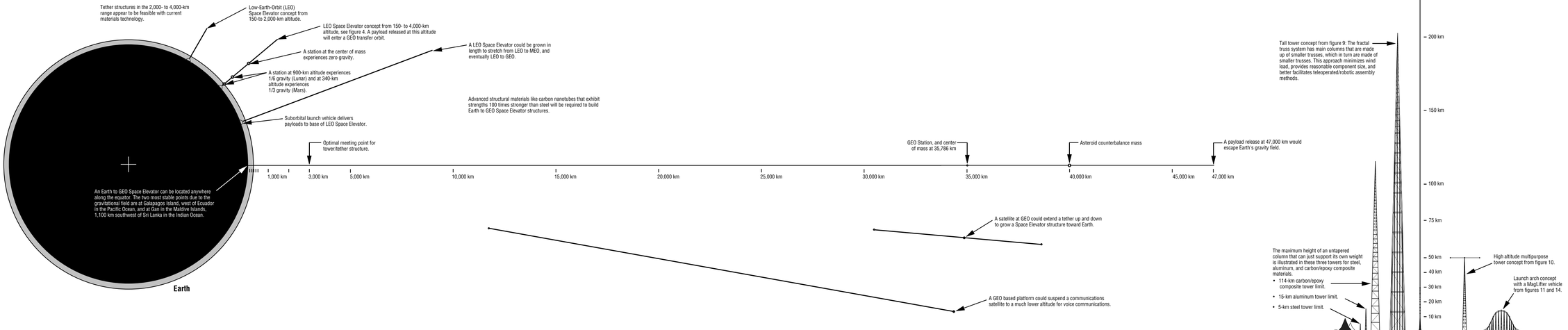
Shea, J.H.: "Sky-hook," Reply by Isaacs et al., *Science*, Vol. 152, p. 800, 1966.

Tsiolkovski, K.E.: "Speculations About Earth and Sky and on Vesta," Moscow, Izd-vo AN SSSR, 1959; Grezi o zemle i nebe (in Russian), Academy of Sciences, U.S.S.R., Moscow, p. 35, 1999.

Von Tiesenhausen, G.: "Tethers in Space: Birth and Growth of a New Avenue to Space Utilization," *NASA TM–82571*, Marshall Space Flight Center, 1984.

Yakobson, B.I.; and Smalley, R.E.: "Fullerene Nanotubes: $C_{1.000.000}$ and Beyond," *American Scientist 85,* pp. 324–337, July/August 1997.

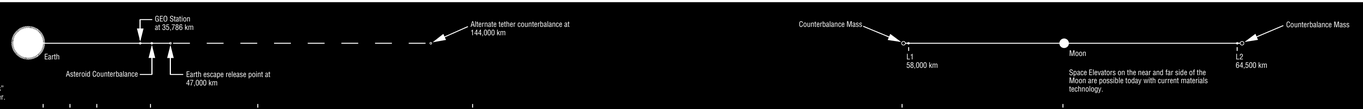
Space Elevator Schematics



Space Elevator Schematics has been prepared for the NASA/CP—2000–210429 "Space Elevators An Advanced Earth-Space Infrastructure for the New Millennium"

This report and schematics are based on the findings from the "Advanced Space Infrastructure Workshop On Geostationary Orbiting Tether 'Space Elevator' Concepts" held in June 1999, at the NASA Marshall Space Flight Center.

Compiled by
D.V. Smitherman, Jr.
NASA Marshall Space Flight Center



Space Elevators on the near and far side of the Moon are possible today with current materials technology.

Lunar distance from Earth varies from 356,410 to 406,697 km.

Three of the world's tallest structures:

- 629 m, tallest stayed television transmitting tower, Fargo, North Dakota
- 553 m, tallest freestanding structure, CN Tower, Toronto, Canada
- 452 m, tallest office building, Petronas Towers, Kuala Lumpur, Malaysia.

The tallest mountain, 8.8 km, is Mount Everest and the deepest ocean trench, 11 km, is in the Mariana Trench in the Pacific Ocean.

This Space Elevator concept, from figure 2, is supported from an ocean platform. High-altitude balloon structures provide possible support and stabilization through the upper atmosphere. The space segment of the structure consists of future carbon nanotube tension structures or PBO pressurized tube segments requiring active stabilization.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operation and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

1. AGENCY USE ONLY *(Leave Blank)*

2. REPORT DATE
August 2000

3. REPORT TYPE AND DATES COVERED
Conference Publication

4. TITLE AND SUBTITLE
Space Elevators
An Advanced Earth-Space Infrastructure for the New Millennium

5. FUNDING NUMBERS

6. AUTHORS
D.V. Smitherman, Jr., Compiler

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

8. PERFORMING ORGANIZATION REPORT NUMBER
M–990

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/CP—2000–210429

11. SUPPLEMENTARY NOTES
This report is based on findings from the Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether Space Elevator Concepts, managed by David Smitherman, Advanced Projects Office, Flight Projects Directorate, NASA Marshall Space Fight Center, Huntsville, AL. The workshop was conducted June 8–10, 1999.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 99
Nonstandard Distribution

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A space elevator is a physical connection from the surface of the Earth to a geostationary Earth orbit (GEO) above the Earth ≈35,786 km in altitude. Its center of mass is at the geostationary point such that it has a 24-hr orbit and stays over the same point above the equator as the Earth rotates on its axis. The vision is that a space elevator would be utilized as a transportation and utility system for moving people, payloads, power, and gases between the surface of the Earth and space. It makes the physical connection from Earth to space in the same way a bridge connects two cities across a body of water. The Earth to GEO space elevator is not feasible today, but could be an important concept for the future development of space in the latter part of the 21st century. It has the potential to provide mass transportation to space in the same way highways, railroads, power lines, and pipelines provide mass transportation across the Earth's surface. The low energy requirements for moving payloads up and down the elevator could make it possible to achieve cost to orbit <$10/kg. This potential for low-cost mass transportation to space makes consideration of the technology paths required for space elevator construction very important today. The technology paths are beneficial to many other developments and can yield incremental benefits as progress is made toward making space elevator construction feasible. A number of issues were raised and resolved during the workshop that has helped to bring the space elevator concept out of the realm of science fiction and into the realm of possibility. It was found that the space elevator concept is incredibly large and complex, but no issues were without some obvious course of resolution. Given proper planning for the development of critical technologies, it appears that space elevator construction could become feasible.

14. SUBJECT TERMS
space elevator, tall towers, electromagnetic propulsion, tethers, carbon nanotubes

15. NUMBER OF PAGES
48

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
Unlimited