IAC-04-IAA.3.8.2.09

Space Elevator Base Leg Architecture

Peter A. Swan, Ph.D.
Associate Partner
Teaching Science and Technology, Inc. – USA
Dr-swan@cox.net

ABSTRACT

While the Space Elevator stretches for 104,000 kilometers, the region of most concern, from the survival perspective, is 2,500 kms and below. The threats inside this dangerous arena include debris, spacecraft, meteorites, lightening, winds, rogue waves, aircraft, and intentional human acts. This paper will address two major questions that will influence the overall systems architecture of a Space Elevator. While the deployment phase of the development of the Space Elevator will only have a single ribbon from the surface of the Earth to well beyond the Geosynchronous altitude, a mature Space Elevator must never allow a complete sever of the system. Indeed, the development team must start with the expectation, and express it in a vision, that there will be no severing of the Space Elevator throughout its lifetime. Design approaches, materials selections, international policy development and assembly must ensure that the integrity of the Space Elevator be maintained. The trade space analysis will address the probability of an individual ribbon being severed, the length of time to repair, and the potential for a catastrophic Space Elevator cut. The architecture proposed for the base leg portion will address two questions:

Shall there be multiple base legs to 2,500 kms altitude?
Should the anchor be based on land or at sea?

INTRODUCTION

There is a tremendous trade space open for the design of the lower 2,500 km of a Space Elevator. While the deployment phase will have the ribbon respond as a spacecraft, the Wright-Flyer and the Mature Space Elevator will require attachment to the Earth. (see Figure 1, Developmental Phases) There are three basic questions that must be addressed when designing of the lower portion of a Space Elevator.

- Can the anchor be off Zero latitude?
- Should the Anchor be located on land or at sea?
- Should there be one base leg or many?

Latitude Allowance

Over the short history of the engineering design for a Space Elevator, the assumption has always been that the terrestrial end must be at zero latitude. This has been coupled with the idea that the nadir point of the geosynchronous location is essential for stability. Further analysis leads one to believe that the initial "grounding" of the long ribbon at the end of the deployment phase must be at that nadir location; however, once the Wright-Flyer is initiated, the basic location can move off the equator. The preliminary answer from early analysis seems to be "yes," with the appropriate compensation for the total Space Elevator beyond the GEO location. This capability could provide flexibility to the location of the anchor station and could allow dynamic coupling to negate natural modes of motion.

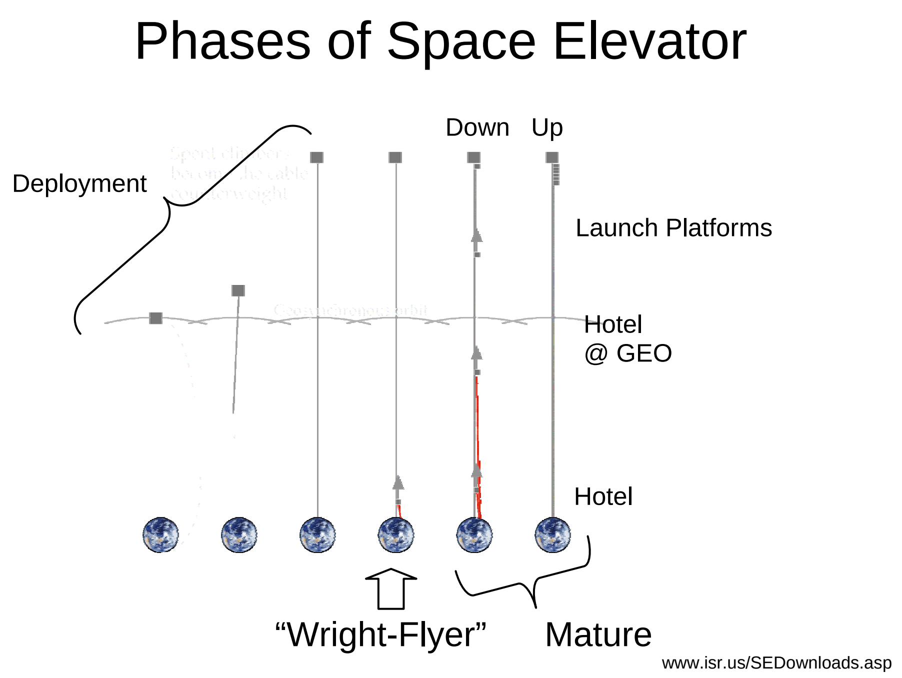
However, the question requires a large simulation that incorporates each element of the Space Elevator (an element could be one meter in length), all the masses attached to the ribbon (hotels/nodes/logistic centers), and of course all the moving climbers. This question is a second level issue until the basing options are refined to a more precise level. This paper will assume a location on the equator for the major anchor point of the base leg segment, with the option of future motion off nadir.

LAND OR SEA BASED

The analysis of this question results in trades crossing both management and engineering disciplines. Both of these areas will be addressed with trades identified; however, the final design consideration will be influenced by the stakeholders and financers. The Space Elevator architect must ensure that all factors are considered to include items that do not influence engineering designs, because these could dominate. A likely determinate for location will be financial investors and return on investment.

Land Based Option: A current idea is that the top of a tall mountain would enable the team to start the trip at a higher altitude, further from the center of gravity. The anchor could easily be tied to the ground so that the base would not move. There are several mountain tops close to the equator that could be a base location. The advantages are leveraged from high altitude starting location vs. the difficulties of working at the altitude in the cold with low oxygen content and immature transportation infrastructure.

Sea Based Option: A similar idea to the land based anchor is a sea based floating anchor infrastructure. The strengths are based around the heritage of the sea with its own laws, history of political insulation, and background of logistics strengths for simiple long distance transportation with proven technologies. In addition, there are expanses of the ocean that are open and usable with minimal impact to current human endeavors. Dr. Gardner presented a solid answer to the where at sea question at the Second Annual International Space Elevator Conference. He showed that there was a location 2000 km west of Ecuador that had minimum lightening strikes per year per square kilometer (as shown in Figure 2), very low probability of hurricanes and cyclones, and almost no wave issues. In addition, there are locations in this region that have very high percentage of cloud-free days for efficient laser power transmission (as shown in Figure 3).



	Deployment Phase	Wright-Flyer Phase	Mature SE Phase
Start	Partial funding	First Ribbon Climber	First Human Climber
End	Solid anchor with stable 1st strand	First Human Climber	Continuous Commercial success
Steps	Authorization to initiate Funding Profile Design Production of Segments First Launch (multiple if necessary) Deployment down and up Attachment to Earth at anchor Stable Space Elevator	Stable Space Elevator Run second strand for safety Run Weavers Attach Safety straps Place logistics stations Run first cargo climber Revenue producing climbers	Design Production Eliminate radiation belts Ensure safety of Space Elevator (human rating) Deploy hotels and logistics climbers First Human climber – probably workers First commercial human climber Commercial success Hotels successful Human spaceflight to Moon and Mars Additional Space Elevators developed

Figure 1, Development Phases

Trade Space for Anchor location:

Table 6.1 shows the trade matrix comparing land and sea based alternatives. This analysis looks at the management side as well as the engineering side. The breakouts cover sovereignty issues, personnel issues, engineering issues and, especially, risk trades.

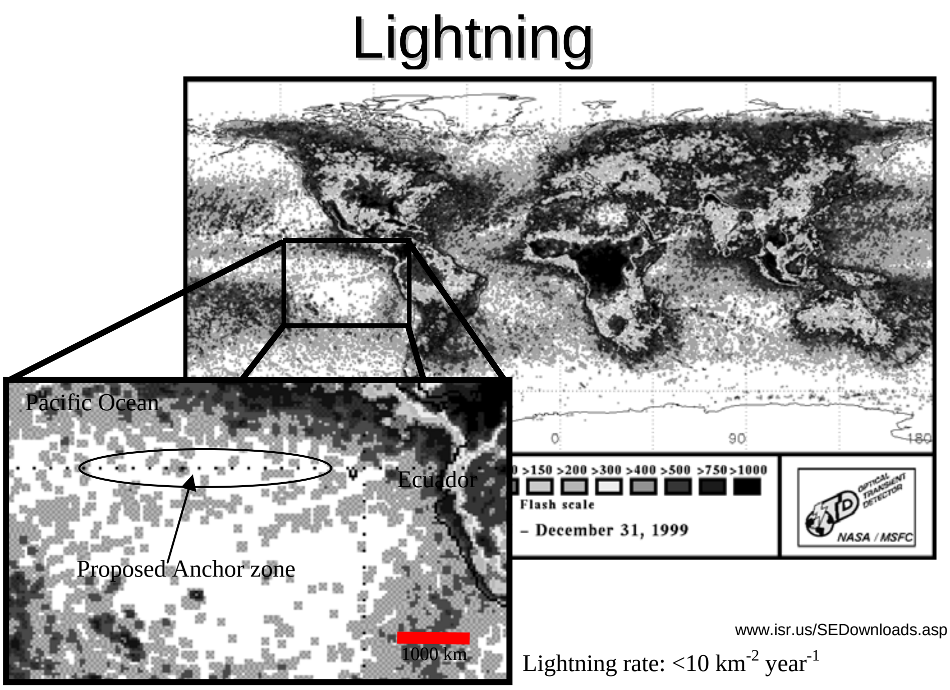


Figure 2, Lightening Rate Image[1]

Table 1, Anchor Locations – Sea vs. Land

	Land Based	Sea Based
Management		
Sovereign Country Vs. Law of Sea	Laws of Nations Sovereign rights Ownership Influence Minimizes International control Access control to project Political upheaval	Large open areas Adapt oil platforms International Laws of the Sea Traditional logistics simplicity (ships and tugs)
Personal Issues	Passports Local laws Local customs Languages Nationalization	Freedom of access Work permits easy Work rules dominate Project focus infrastructure
Engineering		
Top of Mountain vs. Sea Surface	Access issues Road/railroad to top Support infrastructure Weather problems	Open area (400 km radius) Easy movement Ship anchors proven Engineering history (ships) Quiescent weather patterns (2000 km west of Ecuador)
Risk	No local personnel	Open areas for damage control
Anchor Duplication	Every mountain different Transportation infrastructure varies	Anchors can be identical Transportation easy

[1] Gardner, Joseph. "Where on Earth? Chosing an Anchor Point," 2nd Annual International Space Elevator Conference, Oct 2003, Sante Fe, NM.

This table leads one to the conclusion that operating in a hostile environment, like a top of a mountain, has major disadvantages while a sea based anchor lends itself to leveraging the heritage of sea based transportation and logistics. One interesting option would be the combination of land based and sea based to leverage the strengths of both.

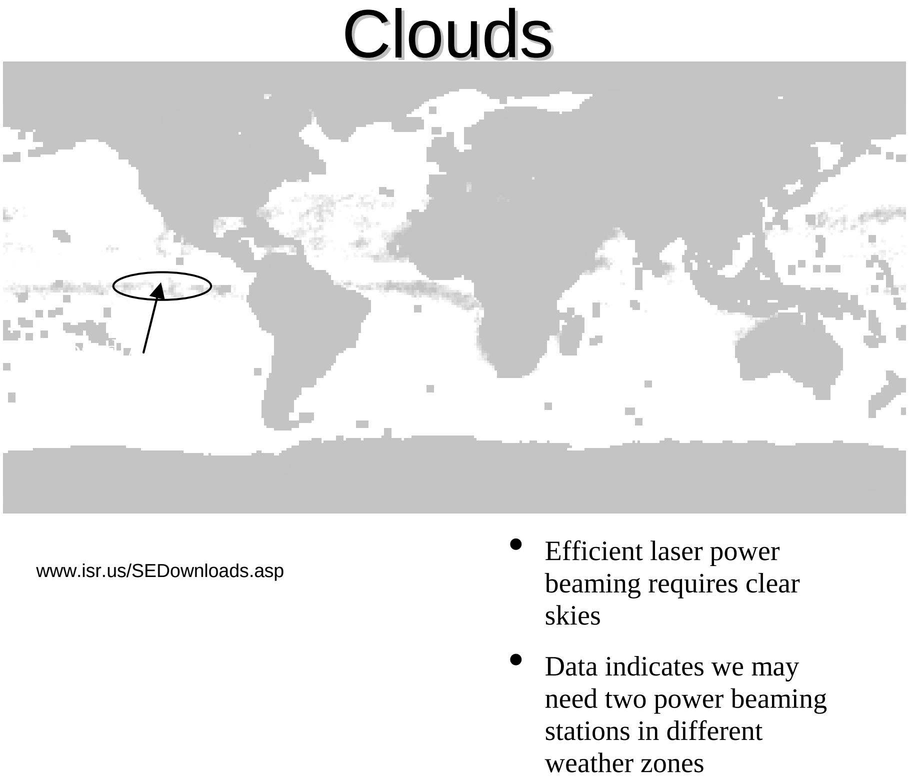


Figure 3, Cloud Densities[2]

[2] [2] Gardner, Joseph. "Where on Earth? Chosing an Anchor Point," 2nd Annual International Space Elevator Conference, Oct 2003, Sante Fe, NM.

NUMBER OF BASE LEGS

Most of the discussions in the past have assumed a single string attached to the Earth to anchor the space vehicle based at GEO for an Earth based bridge to the stars. Indeed, the deployment and early Wright-Flyer phases of the Space Elevator will have a single ribbon attached to the Earth. The development of the full ribbon capability from a single strand during the Wright-Flyer phase is essential because the threats to the Space Elevator below 2,500 km are much greater than above that altitude. A simple back-up strap in parallel with the Space Elevator will not be sufficient in the lower altitudes. Multiple mitigation efforts are required to ensure that the "Zero Cut" policy is implemented.

Requirements and Needs: In a parallel paper (Survival of the Space Elevator), many threats were outlined along the ribbon and broken out with respect to altitude regions. The mitigation techniques were explained for the threats discussed (mainly orbital objects and meteorites) with the purpose of showing that the Zero Cut policy could be ensured by proper analysis, design and execution. However, the lower portion (below 2,500 km) has additional threats and operational requirements. Some of these are:

Survive high winds (hurricanes /cyclones /tornados)
Survive lightening (cloud to cloud and cloud to ground)
Survive local environment (rouge waves or snow and ice)
Survive aircraft accidents
Survive land/sea vehicle accidents
Survive deliberate human attempts to sever
Enable up traffic to gain velocity
Enable down traffic to slow down
Support "weekend hotel" at 100 km altitude
Support logistics node at 2,500 km
Support recreational travel
Move Space Elevator for large space objects (reel in/out each leg)

Trade Space for Number of Base Legs: The ability to ensure a Zero Cut policy encompasses tremendous issues, threats, probabilities, needs, mitigation approaches, repair approaches, and time to repair. To ensure a Space Elevator that is not severed, the design of the system must respond to the environment that it will endure and provide the safety that is expected from an elevator. Table 2 shows a trade space analysis that is preliminary and probably missing some items; however, it sets the stage for a follow-on study establishing the number of base legs required to support the Zero Cut policy.

The probability of an accident with people is remote and can be shown to be zero. However, the threat of terrorists or disgruntled employees is real and must be assessed. In addition, nature with its winds and lightening have measurable threats and must be accounted, and planned for. The density of the meteorite and debris threats lead to hits per year that are estimated from the community with respect to meter cross section probabilities. This initial estimate is probably very preliminary as the community has always dealt with orbital velocity objects passing each other at great speeds. The Space Elevator will be stationary (with respect to the Earth) and the number of collisions must be calculated with new baseline assumptions included. The active spacecraft in LEO are a threat and must be dealt with so as to eliminate the probability of collision. This can be accomplished with the proper support from the international community. The concept of the Space Elevator corridor and the need for the Zero Cut policy will enhance the argument of the management team working in the international community.

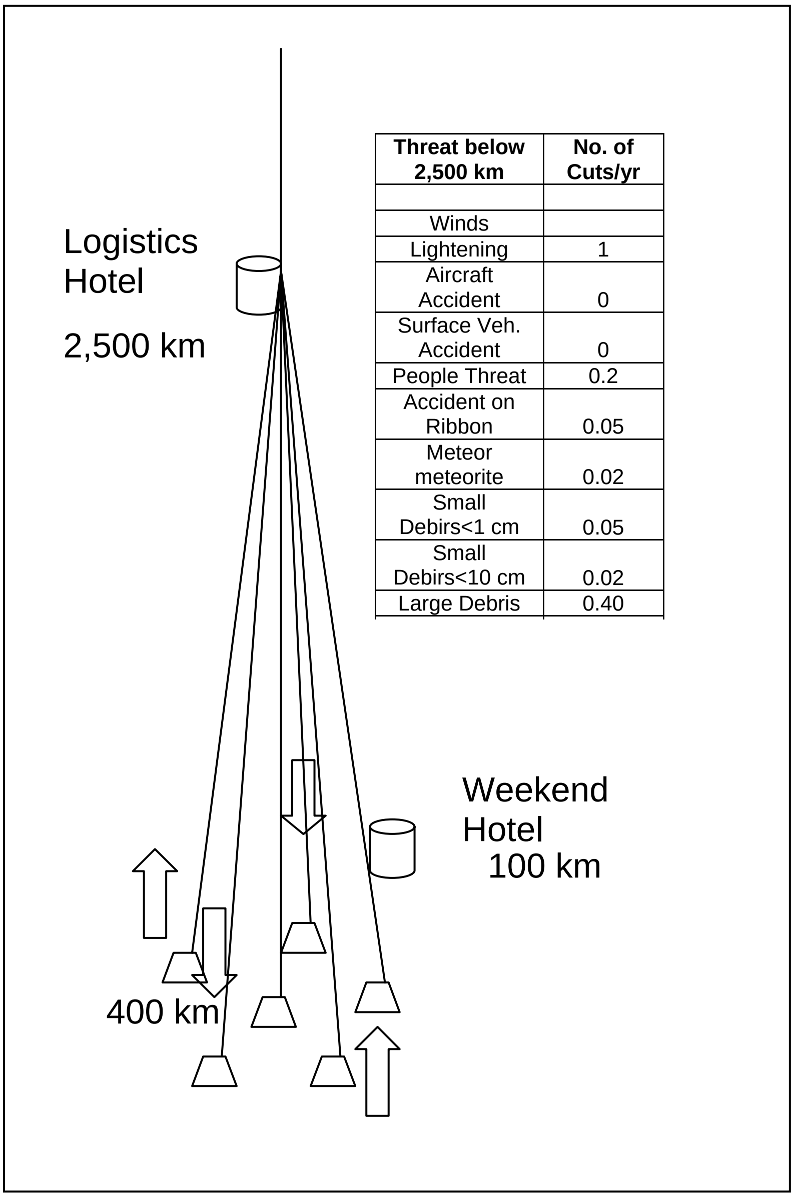
Table 2, Vulnerability Trade Space

Threat below 2,500 km	Probability of Event(no fix)	Probability of Cut	Height of Cut (km)	Mitigation Technique	No. of Cuts/yr
Winds	very small	~ zero			
Lightening	measurable	100%/leg	< 30	>1 leg	1
Aircraft Accident	very small	~ zero	< 20	flight control	0
Surface Veh. Accident	very small	~ zero	surface	restrictions	0
People Threat	measurable	100%/leg	< 30	security	0.2
Accident on Ribbon	measurable	20%	< 2,500	safety	0.05
Meteor meteorite	3 hits/day	0.002	< 2,500	design	0.02
Small Debirs<1 cm	10 hits/yr	0.005	< 2,500	design	0.05
Small Debirs<10 cm	2 hits/yr	0.01	< 1,500	design	0.02
Large Debris	1/2 yrs	80%	< 1,500	move SE	0.40
Active Spacecraft	measurable	90%	< 1,500	prediction	0.005

Number of Base Legs: After a full analysis of the trade space over the next few years, the recommended design will surface defining how many base legs will support the needs and requirements. This paper will estimate that the base leg architecture will look something like Figure 4, Base Leg Architecture. This includes five legs spread around the center anchor. That architecture could be a total of six legs with six anchor points. The distances of the pentagon shaped anchor pattern would probably be large enough to have multiple legs outside of the highest winds of a hurricane. This would probably ensure that lightening patterns were confined to one or two base legs. In addition, rouge waves and mountain tops are not usually close together. The estimate for this separation is 400 km from center base leg to circumference base legs.

Recommended Architecture

For the Earth terminus of the Space Elevator, various factors dominate the analysis. The need for a free space of 400 km pentagon shape, the need to interface with terrestrial transportation, and the political freedom afforded to international endeavors drive the decision toward a multi-leg architecture that is sea based. Many studies have been conducted looking for the proper placement along the equator. Future studies must be conducted to pinpoint the location and analyze the orbital dynamics issues at that longitude. Therefore, the recommended answer from this paper is along the equator, west of Ecuador, with six base leg anchors with radius of 400 km from center terminus, perhaps centered on an island.



Threat below 2,500 km	No. of Cuts/yr
Winds	
Lightening	1
Aircraft Accident	0
Surface Veh. Accident	0
People Threat	0.2
Accident on Ribbon	0.05
Meteor meteorite	0.02
Small Debirs<1 cm	0.05
Small Debirs<10 cm	0.02
Large Debris	0.40

Figure 4, Base Leg Architecture Option