Comparison of Current Architectures
[as of summer of 2016]

Space Elevator Architectures have matured since their introduction in the last decade of the 19th century, shown in the 20th century with science fiction expanding many concepts, and finally with modern day designs during the first two decades of the 21st century. Comparison of published architectures for space elevators is based upon a few criteria:

1. Publishing, and distribution of each concept created significant steps in the development of space elevators,
2. The engineering level of detail was appropriate for the phasing of each report,
3. The presentation showed as much of the engineering as possible, enabling credibility for the development of space elevators.

Konstantin Tsiolkovsky, a Russian rocket scientist, pioneered astronautics’ theory in general and specifically conceptualized a building growing to GEO orbit, in 1895 [Tsiolkovski, 1959]. This particular concept focused on aspects of the Geosynchronous orbit. This led to a series of five space elevator architectures over the last 75 years. The first two were significant leaps in understanding, while the last three have lead to the current breadth of concepts:

• In 1960, Yuri Artsutanov presented a real approach visualizing how it could be achieved – a big leap from Tsiolkovsky’s concept.
• Then, in 1974, Jerome Pearson resolved many issues with engineering calculations of the required tether strengths and various approaches for deployment. This was, once again, a leap beyond Arsutanov’s work and set the stage for the “modern design” for space elevators.
• Dr. Edwards established the current baseline for designing space elevator infrastructures at the turn of the century with his book: “Space Elevators” [Edwards, 2002]. He established that the engineering could be accomplished in a reasonable time with reasonable resources. His baseline is solid; and, it was leveraged for the next two refinements of this transportation infrastructure concept.
• The International Academy of Astronautics used Dr. Edwards’ design and the intervening ten years of excellent development work from around the globe. Forty-one authors combined to improve the concept and establish new approaches, expanding the Edwards’ baseline.
• The most recent version of space elevator architectures is the recently released view by the Obayashi Corporation. Their set of assumptions of the study established stricter requirements and resulted in a longer developmental period with increased payload capacity.
Origin & Architectures # I & II – Inventor’s Concepts

Konstantin Tsiolkovsky wrote about building a tower on the equator in an essay. His concept was to build up from the ground with sufficient length to reach the GEO arc. The first player in the field to really deal with cables and layout a real concept was Yuri Artsutanov, who showed that you could stretch a cable from GEO down if the strength and lightness was significantly better than existed in 1960. [Artsutanov, 1961]

Figure 1, Artsutanov Article.

In 1975, Jerome Pearson published his engineering calculations showing that the space elevator could be stable and built from a GEO orbit. [Pearson, 1975] His image is in Figure 2. As such, both Yuri Artsutanov and Jerome Pearson are considered co-inventors of the space elevator. These two architectures were remarkable in their time and set the stage for the next three “modern day” transportation infrastructures.

Figure 2, Space Elevator, Pearson, 1975
As these two are the co-inventors of the space elevator concept, they discuss their ideas whenever they are together.

Figure 3, Pearson and Artsutanov comparing notes

Architectures # III – Dr. Edwards’ Architecture [2002]

The book “Space Elevators” by Dr. Brad Edwards and Eric Westling revolutionized the concept of a transportation infrastructure for space access with the realization that it could actually be built, assuming that the carbon nanotube material developed as expected. The engineering design was solid and showed how the proposed space elevator interacted with the environment. The gravitational factors, radiation, heat/cold quandary, space debris, lightning and other atmospheric effects were all addressed and answered to an introductory level. The basics of the design are shown in the image on the right; and, a summary of the major items are shown below:

Figure 4, Dr. Edwards Basic architecture

- Length: 100,000 km, anchored to Earth terminus, as a large mass Marine Node, and connected to a large End Node [Could be an asteroid]
- Ribbon: Width-One meter, curved;
- Design- Woven with multiple strands and curved;
- Material-Carbon Nano-Tubes with 100 GPa strength at 1.3 gm/cm³
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- Cargo: 20 metric ton payloads without humans
- Loading: Seven concurrent climbers on the ribbon
- Power Source: Terrestrial Lasers
- Marine Node: Ocean going oil platform
- Operations Date: The space elevator can, and will, be produced in the near future [Ten years after start with mature materials].
- Construction Strategy: The first space elevator will be built from GEO; then, once the gravity well has been overcome, it will be replicated from the ground up.
- Price: $6 billion USD
- Cost per kg: $150 USD

Figure 5, Tether Climber with Laser Energy

Architectures # IV – International Academy of Astronautics [2013]

The IAA initiated a study in 2009 to evaluate the latest aspects of a potential low cost access to space infrastructure. The global effort included 41 authors, with 5 editors, from around the world and across many academic disciplines. The effort pulled together a 350 page book that addressed improvements to the architecture from Edwards’ Baseline. One consistent assumption was that human traffic on the space elevator would be at least a decade after the first few space elevators. The major differences are explained after a quick summary of the baseline configuration [Swan, 2013]:

- Length: 100,000 km, anchored to floating Earth terminus, with a Marine Node connected to a large Apex Anchor.
- Ribbon: Width-One meter, curved;
- Design: Woven with multiple strands and curved;
- Material-Carbon Nano-Tubes with 25-35 MYuri at 1.3 gm/cm3
- Cargo: 14 metric ton payloads without humans [tether climber 6 MT]
- Loading: Seven concurrent payloads on the ribbon
- Power Source: Solar power after 1st 40 km
- Marine Node: Ocean going oil platform or retired aircraft carrier
- First 40 kms: box protection with power from an ultra-light cable.
• Alternant: High Stage One at 40 km altitude
• Apex Anchor: Based upon deployment satellite (with thrusters)
• Operations Date: The space elevator can, and will, be produced in the near future. [2035 operations start]
• Construction Strategy: The first space elevator will be built from GEO; then, once the gravity well has been overcome, it will be replicated from the ground up.

Figure 6, IAA Architecture [Chasestudios.com]

• Architecture: Baseline is one replicating space elevator [used to produce all others] and then pairs sold to operating companies. Initial concept: three pairs operating around the world.
• Price: $ 13 billion for first pair, after replicator space elevator.
• Cost per kg: $ 500 USD

Figure 7, Box Protection above Atmosphere [chasestudios.com]

**Improvements:** The improvements from older architectures were based in four significant parts:

**Part 1 – Atmospheric Protection:** The first forty kilometers of atmosphere are highly dangerous with all the normal factors such as lightning, high altitude winds, rain, sleet, and snow. As a preferred solution, the protective box tether climber was introduced. The initial tether climber would be no more than a storage box protecting the sensitive mission climber and solar arrays folded inside. The image to the right
shows the deployment of folded solar arrays and tether climber as they climb out of the protective box. This enables the designers to protect mission climbers in a box within the atmosphere and release them as a free climbers above the atmosphere. This simplifies the design and enables the mission climber to be much less complex in design. In addition, an alternate Marine Node design was considered which included the innovative approach to the same problem by developing a High Stage One. This solution used mechanical energy to hold up a series of evacuated tubes leading to a work platform at 40 kms that is able to support over 400 metric tons without impacting the load on the space elevator tether.

**Part II – Lowering of needed tether strength level:** Recent analyses of the whole problem showed that there were many trades to be evaluated: an example trade is the strength of materials to taper ratio with carrying capacity of each tether climber vs. material strength. A large study was conducted by Ben Shelef that ended up with a Space Elevator Feasibility Condition trading many factors against each other trying to optimize the design of the total system. As a result, the required level of material strength for a feasible space elevator turned out to be 30-35 MYuri. This is roughly 40 GPa [with density of material accounted for] with a safety factor of 40% [standard Aerospace safety factor]. The needed material strength was about one third the numbers being looked for within the Edwards’ approach. This moved the delivery date of sufficiently robust material forward. This enabled the program schedule to be drawn as shown in Table 1. The realization of this infrastructure development is shown in this flow diagram. The dates are estimates with the assumption that the whole system would be initiated around the start of the next decade.

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Table 1, Schedule for IAA Roadmap [Minoru, 2014]

**Part III – Solar Power Only:** The IAA study concluded that space elevator tether climbers could climb to GEO [and beyond] with solar power only. This assumption was developed after two studies were conducted. Again, Ben Shelef looked at the numbers and concluded that solar power could work. The second analysis was conducted for the IAA and showed that if lightweight solar arrays for space that are projected by the current experts are, in fact, available on schedule [see documentation in IAA report], there would be sufficient power to
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raise a 20 Metric Ton climber, even in the heavy gravity at the 40 km altitude location. The tether climber now worked with the concept of constant power and varied its speed as gravitational forces lessened.

Figure 8, Folded and Deployed Solar Arrays [chasestudios.com]

The numbers are given for the needed area of solar arrays to provide the power required to move the tether climbers fast enough to make it to GEO within a week. Indeed, the arrays are large; but, the space industry has been dealing with asymmetric structures in space for the last 60 years; and, they expect no show stoppers when using solar arrays as the only power source above 40 kms.

**Part IV – Apex Anchor is Smart:** The previous architecture estimated that the counterweight could be an asteroid. The IAA study needs far more capability at the Apex Anchor; so, there is a demand for thrusters, computers, and communications at the upper tether terminus. This requires that the Apex Anchor be smart vs. dumb. The functional requirements include moderating the dynamic motion at the end point, reeling in and out to establish appropriate motion, and emergency force application if there is a tether sever. A smart Apex Anchor could contribute to the control of the remaining tether.

**Architecture V – Obayashi Architecture [2013]**

The Obayashi Corporation investigated space elevators as a low cost access to space and showed its approach to develop a space elevator infrastructure. [Ishikawa, 2013] The infrastructure that resulted from this study is quite different and far more robust. However, when one looks at the initial requirements of their study, the results are reasonable and very consistent with the two previously conducted detailed architectures. The going in position for this most recent study was that human cargo would be scheduled during some of the first tether climber operations. The inclusion of humans was a basic requirement driving the design. The major differences are based upon this requirement.

**Change One: Human transport** – this requirement drove the need for 150 GPa of tether strength and the design of multiple tethers for each space elevator. In
addition, the tether climbers consisted of many “cars” that carry people as well as payload. These requirements drove the design.

**Resulting changes:** The tether strength requirement was much larger, the number of cables per elevator increased, there is a tie to an island with the ground node, and there is a small aerodynamic shaped climber that goes through the atmosphere. All of these changes are additional to the baseline space elevator they plan on deploying first. This baseline single tether is very similar in design to the basic space elevators of both Dr. Edwards and of the IAA study. As such, the essence of the developmental program is the same, with a more robust design building gradually, resulting from higher demands to support human transport. The details are as follows:

- **Length:** 96,000 km, anchored to an Earth terminus, with a Marine Node, connected to a large counterweight [12,500 ton]
- **Ribbon:** Width-half meter, curved; with 2 cables per carrier
- **Design:** With many cables leading to massive tether climbers
- **Material:** Carbon Nano-Tubes with 150 GPa capability
- **Loading:** Six concurrent payloads on the ribbon [both up/down]
- **Power Source:** Laser power from ground or space
- **Marine Node:** Port extension from island, 40 million MT, 400 m diameter
- **Climber:** 100 MT, with 79 MT payloads
- **GEO station:** 66 modules at 4,000 MT
- **Operations Date:** The space elevator can, and will, be produced in the near future. [2055 operations]
- **Construction Strategy:** The first space elevator will be built from GEO: then, once the gravity well has been overcome, it will be replicated from the ground up. First cable in 17 years, large capability after 18 years of building up cable.
- **Architecture:** One large space elevator with maximum capability
- **Price:** $100 billion USD
- **Cost per kg:** $50-100 USD

The next few figures show some of the concepts for this third “modern day” space elevator architecture. The Obayashi Corporation images show the GEO Node with human occupancy, a tether terminus platform and an Earth Port with undersea tunnel, and program schedule layouts.
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Figure 9, View of the human space elevator at GEO Node (Illustration)

Figure 10, Earth Port (main facility)

Figure 11, Earth Port (onshore main facility and offshore supporting facility)
Table 2, Construction Schedule, Obayashi Concept

References:

- Fitzgerald, M, et.al, Space Elevator Architectures and Roadmaps, lulu.com, 2015
- Minoru SATO, Akira TSUCHIDA, Review of the Space Elevator Research in Overseas, draft paper shared with author.

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