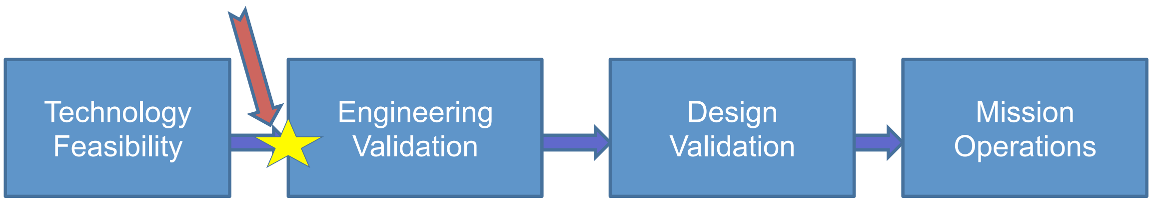
Starting Now! Space Elevators Entering Engineering Development



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Engineering Compilation
Workbook: First Draft
as of 8 Mar 2021

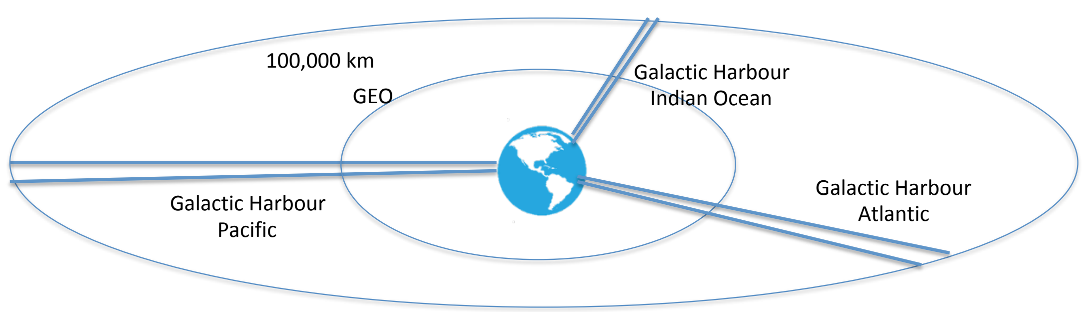
A Primer for Progress in Space Elevator Development

Preface

This working document has been in development for years. The basic elements come from the vast body of knowledge accumulated since ISEC initiated its collection and creation of modern day Space Elevator research and development (2009). The current situation is that the development of Space Elevators is prepared to move into the second phase, or Engineering Validation. As such, there must be a document that pulls together the vision, engineering and architecture aspects to focus the efforts of the many who follow. This working document should be able to mature at a rapid pace with all the inputs from the Space Elevator community. There are three key messages that should be evident while reviewing this document, which should also set the stage for growth of the project:

> Message One: The engineering team is initiating the Space Elevator Development program and starting Engineering Validation.
>
> Message Two: Dual Space Access Architecture strategy will leverage the strengths of both advanced rockets and Space Elevators which will accelerate the successful completion of future missions.
>
> Message Three: Our vision to be the Green Road to Space matches the dreams of many and will enable such dreams with its capability to move massive tonnage to GEO and beyond. We plan on being the second lane in the future highway to space.

This future vision shows six Space Elevators within three Galactic Harbour delivering 170,000 tonnes to GEO and beyond.



Acknowledgement

Note: This Working Document will be continually improved and updated as the information surfaces. The basic purpose is to show the path to reach the destination, an operational mega-project called the Galactic Harbour with two Space Elevators.

Note: In addition to this document, there is a tremendous amount of "body of knowledge" on the ISEC website: www.isec.org

The Modern Day Space Elevator has refined itself over the last three years and is ready to begin engineering validation testing.

Executive Summary:

If one were to think of Space Elevators as evolutionary in humankind's departure from the Earth, then one starts to recognize - that as with all journeys - the classic FIRST STEP must be taken. WE ARE TAKING THAT FIRST STEP NOW. The Space Elevator is revolutionary in that it changes the equation of delivery. The dynamics of massive tonnage versus the "limiting" rocket equation becomes the liberating movement of logistical cargo by electricity, while fulfilling customers' needs. It has so many promises, and is seen as an enabler for so many dreams, that it must be pursued. Now. These dreams are important as they lead to specific visions of what can be done and are then transformed into need statements for developmental projects. Dreamers make things happen as much by spreading their enthusiasm early in a program. What we need are dreamers who stimulate the rest of us to action. The vision that is driving the Space Elevator community is:

Space Elevators are the Green Road to Space while they enable humanity's most important missions by moving massive tonnage to GEO and beyond. This is accomplished safely, routinely, inexpensively, daily, and they are environmentally neutral.

The ISEC team has been assessing the technology feasibility situation since 2008. In recent times, the team has begun an open dialog with those members of industry, academia, and others; who could be the deliverers of ISEC solutions. Industry (especially) will show how the needed technologies are being matured and when they could be dependably available. These readiness assessments are the Phase One exit criteria.

The Space Elevator community has arrived at two current realities:

1) There should be a Dual Space Access Strategy which is a partnership between future rockets and space elevators. The strengths of rockets will open up the Moon and Mars, while continuing to satisfy orbital needs around the Earth. In the near future, Space Elevators will become the second road to space by moving massive amounts of cargo to grow the environments at GEO, the Moon and Mars. This partnership will leverage both strengths and enable humanity's bright future.

2) The Space Elevator is closer than you think and is entering the Engineering Development Phase after successfully completing multiple Preliminary Technological Readiness Assessments (PTRA). Note; a reference? Not in the ones listed

As such, the Space Elevator is entering Phase Two of Development, which is to Validate Engineering Approaches. This Phase has begun soon after several successful PTRAs. One of the first steps will be for the Space Elevator team to assign a wide range of engineering validation objectives to various members of the industry base. Some efforts will reflect the foreseen competitive construct of the acquisition plan to be submitted by Milestone A. The Phase two activities are driven by six major statements:

- Can it be built? This question can be answered with the following activities: a) Determine the engineering approaches being considered by industry, b) Ask industry to show how their engineering approach is valid, and c) Describe approach incorporating ongoing technology maturation.
- Examine Industry's Program Roadmaps: this would include determining the range and number of needed engineering validation tests and demonstrations.
- Assess schedule and technical risk: always a very near-real time assessment.
- Delineate on-ramp criteria towards Initial Operations: the question becomes one of when will the needed capability be ready?
- Design Validation requires establishment of criteria and standards.
- Expected technical performance must be base lined by the end of phase II.

The ISEC community believes strongly that it is necessary to initiate development of the Space Elevator now. ISEC, as a small 501(c)(3) consortium, has a mission to support development of Earth Space Elevators. The approach has been to develop a necessary body of knowledge sufficient for the initiation of a Space Elevator development program. We believe that as we move into the third decade of this century, the implementation of a Space Elevator architecture is essential to support humanity's needs and dreams - Now. Indeed: Space Elevator research has grown the body of knowledge exponentially since 1998. The Space Elevator program is prepared to proceed into engineering development. This compelling story illustrates how Space Elevators are ready to enable the visions of many.

***"We are ready to initiate the Space Elevator mega-project,
Now -- the technologies are available."***

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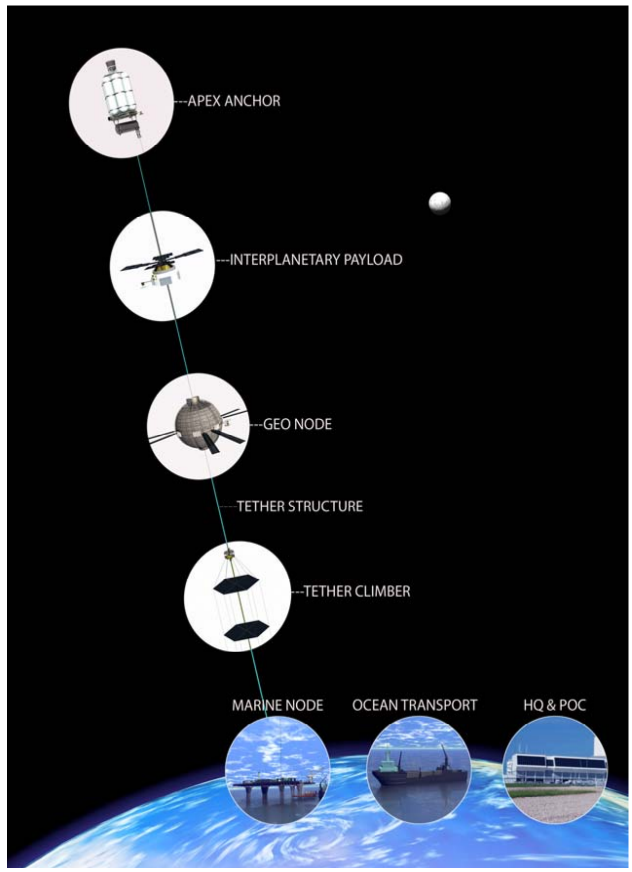
Chapter One: Start NOW!

1.0 Introduction:

It has been realized that the Space Elevator development must be started immediately for three critical reasons:

1. The Promises of Space Elevators are so revolutionary!

2. We can now build an Earth Space Elevator as the tether material has been identified and will be available for construction, and
3. Space Elevators are essential to the future of mankind.



Space Elevator Transportation Infrastructure (IAA 2014)

These points will be expanded upon in this report with multiple references to completed investigations, research, studies and projects. The large body of knowledge collected over the last 23 years (1998-2021), leads to the conclusion: *"We should start today and move Space Elevators into Engineering Development with segment level testing."*[1?]

March 2021 Announcement:

Earth Space Elevators are ready to start engineering development now!

[1] ?Fitzgerald Conversation 3 Feb 2021.

Rationale: "Earth Space Elevators take massive freight to orbit on the Green Road to Space." Space Elevators can fulfill the needs and visions of many. The engineering readiness of Space Elevator technologies is high. ISEC believes Space Elevators are ready to start testing with a demonstrations based developmental program.

When the Space Elevator is operational, access to space will be significantly improved. Historically, mankind has been restricted by the conundrum of rockets: *"How can we use a delivery system that deposits less than 2% of the original mass at the launch pad to its chosen destination (GEO and beyond)?"*

Space Elevators answer the Conundrum of Rockets

The conundrum of rockets is the simple realization that the delivery of mass to its destination is an insignificant percentage of the mass on the launch pad. The glaring example is the delivery of a half percent of the launch pad mass to the surface of the moon for Apollo 11. It is up to 2% for delivery to Geosynchronous Orbit and woefully small for delivery to Mars' orbit, much less Mars' surface. The question is why would you employ a methodology for delivery that only delivers less than one percent to your desired location (lets say the future Gateway around the Moon). The Space Elevator solves that conundrum by delivering 70% of the mass at liftoff (the other 30% is the tether climber and will be reused repeatedly) to GEO and beyond by leveraging electricity.

If one were to think of Space Elevators as an evolutionary approach for humans to leave the surface of the Earth, then one starts to recognize the essential step that must be taken. It is revolutionary in that it changes the equation of delivery dynamics - rocket equation limiting vs. massive movement of logistical cargo - while it fulfills the customer's needs. It has so many promises and is seen as an enabler for so many dreams, that it must be pursued.

1.1 Benefits: What kind of specific benefits could we expect to see from functioning Space Elevators? As with the transcontinental railway, it's impossible to foretell all of the uses of such an infrastructure; however, the delivery of 170,000 tonnes per year to GEO and beyond will:

- Energize the human spirit with robust exploration, investigation, discovery and growth.
- Slow global warming by delivery of Space Solar Power satellites for assembly at GEO every two weeks (9,000 tonnes each) eliminating hundreds of coal and oil power plants. Though there are many debates about the economics of establishing solar power satellites to provide Earth with clean, limitless power, there is no doubt that to do so will require the capability to launch enormous quantities of materials into space. Only a Space Elevator can give us that capability.
- Enable humans to become a multi-planetary species by delivery of Mr. Musk's 1,000,000 tonnes of support logistics to Mars in about six years (vs. 10s of thousands of Star Ship launches). This would provide an insurance policy for humanity, an outlet for those with a pioneering spirit and, almost certainly, increased benefits here on Earth as commerce between our planet and others is established.
- Ensure support logistics for lunar explorers, miners and/or colonists with thousands of tonnes per day of needed supplies with daily, safe, inexpensive, and Earth friendly delivery.
- Enhance environmental improvements by providing a Green Road to Space replacing thousands of launches burning rocket fuel in the atmosphere.
- Enabling large scale manufacturing in a zero-g environment. When corporations can build manufacturing facilities in space at an affordable price, they will do so. Right now, the cost and weight penalties are too prohibitive to even consider the idea.
- Stimulate Space Tourism – A Space Elevator could provide a way that most of us could afford to visit space, and even stay for a while if we wanted to.
- Encourage more and cheaper satellites. Satellite technology has provided all of us with enormous benefits, from DirectTV to weather satellites to increased national security. Being able to lower the cost and increase the reliability of satellite liftoffs will lead to new technologies that we can't even imagine today. Scalable, inexpensive and reliable access to space will benefit all of us and a Space Elevator is the way to get there.

1.2 What is a Space Elevator? A Space Elevator (SE) can be thought of as a vertical railroad into space. A tether (cable) stretches from the surface to an Apex Anchor (counterweight) 100,000 km away that carries cargo (and eventually humans) to and from space. The Space Elevator is the most promising Transportation Infrastructure on the drawing boards today, combining scalability, low cost, quality of ride, massive payload throughput and safety to deliver truly commercial-grade space access – practically comparable to a train ride into space. The massive movement capability, as well as the low cost, ensures that the infrastructure approach is "right."

The Space Elevator Transportation Infrastructure is based on a thin vertical tether stretched from the Earth's surface to a mass far out in space with electric tether climbers that drive up and down the tether. The rotation of the Earth keeps the tether taut and capable of supporting the climbers. The climbers travel at speeds comparable to a fast train, and carry no fuel on board – they are powered by choice, or combination, of sunlight and laser light projected from the ground. While the trip to space takes several days, climbers are launched each day with a first "baseline" design of 20 metric ton climbers. However, as the infrastructure matures by making the tether stronger or thicker, we can grow the Space Elevator to lift 100 metric tons at a time. In addition to launching payloads into orbit, Space Elevators can also use its rotational motion to inject them into planetary transfer orbits – thus able to launch payloads to Mars, for example, each and every day. This release from the Apex Anchor can enable massive movement of cargo and supplies daily and with fast transit vs. Hohmann? only once every 26 months. Imagine the kind of infrastructure we can set up waiting for the first settlers to arrive. Looking back from the year 2100, the construction of Space Elevators will be considered to mark the true beginning of the Space Age, much like the advent of the airplane or steamboat heralded the true commercial use of the air and sea. A complementary infrastructure of rockets and space elevators will make this happen.

1.3 Necessary to Initiate Development:

ISEC is a small 501(c)(3) consortium that has a mission to support development of Earth Space Elevators. The approach has been to develop a necessary body of knowledge sufficient for the initiation of a Space Elevator development program (review BoK at www.isec.org). We believe that as we move into the third decade of this century, the implementation of a Space Elevator architecture is now essential to support humanity's needs and dreams. We will make the bold statement now -

"We are ready to initiate the Space Elevator mega-project --
the technologies are here."

Indeed: Space Elevator research has grown the body of knowledge exponentially since 1998. Now the Space Elevator program is prepared to proceed into engineering development. This compelling story illustrates how Space Elevators are ready to enable the visions of many.

Yes, we at ISEC believe that the Space Elevator is not elective. It is a MUST if our species really wants to develop colonies off planet and improve the health of the Earth. Its particular strength is massive movement of tonnage to high orbit. Seventy percent of the tether climber mass on the ocean surface will be delivered to GEO and/or inserted into fast transit towards the Moon, Mars or other destinations. Our investigations (Arizona State University/ISEC research and International Academy of Astronautics studies) have shown that release from an Apex Anchor enables trips to Mars in as few as 61 days, with departures each day of the year (no 26 month window), and with massive movement of tonnage. (see 2020 ISEC study report "Space Elevators are the Transportation Story of the 21st Century." at www.isec.org)

We have been working diligently over the last 17 years developing the key elements of a mega-project design. The dedication of the Space Elevator teams, each team leader on projects, each presenter at our 15 conferences and each ISEC Board Member has contributed towards our position today. We are ready to proceed and hope to join other visionaries planning to help the human condition. We see Space Elevators as critical to near term visions such as colonies (Lunar orbit, L-5, Lunar Village, and Mars) and also to improve the human condition (Space Solar Power, movement of hazardous manufacturing off planet, and Sun Earth L-1 Solar Shade). We must start planning for development NOW.

The bottom line for this report shows that:

- Space Elevators are essential in the near future.
- The developmental program can, and should, be initiated immediately.

1.4 An Interesting Insight: ISEC is conducting a year-long research study, "The Space Elevator is the Green Road to Space," that has preliminary results that show how essential Space Elevators are. From the environmentalist view: Space Elevators are mandatory, as shown with this list of potential beneficial impacts.

Table:Potential Beneficial Impacts of Space Elevator:

Approach	Effect
Enabling Space Solar Power	Reducing the number of fossil fuel burning plants providing energy (100s of coal plants) by using the delivery of energy from orbit to anywhere all the time
Zero (or negative) carbon footprint to deliver to space	Daily operations, at zero (or negative) carbon footprint, reduces the environmental impact of the expected massive movement to space.
Enable Appropriate Solar Shade at L-1	Reducing the energy from the Sun that reaches the Earth's Atmosphere, thus reducing global warming.
Reduce Burning of fuel in Atmosphere	Replacing number of rocket launches (such as to support humanity's movement off planet) will decrease pollution significantly.
Environmentally Friendly Space Infrastructure	Provides safe, reliable, routine, daily, environmentally friendly, and inexpensive transportation infrastructure to move massive tonnage to GEO and beyond, specifically the Moon and Mars.
Enable Permanent Disposal of High Level Nuclear Waste	Deposits Nuclear Waste in Small Solar Orbit which provides safe and long term storage of High-Level Nuclear Waste.

Chapter Two: Dreams and Visions of Off-Planet

2.0 Multiple visions merging towards satisfying humanity's needs

2.1 Dreaming Big Leads to Strategy: The space community is in the middle of having big dreams. Over the last six or seven years, it has been obvious that the human race would be moving off planet - first to the Moon and then on to Mars. This series of big dreams has been pushed by NASA's successes, international missions to Mars, the back side of the Moon and commercial development of visions for companies and/or individuals. A few are: Mr. Musk's expectation of a Colony on Mars with up to a million settlers, Mr. Bezos's statement that he is building the road to space for the next generation, and the National Space Society's vision of millions of people living and working beyond Earth.

The Space Elevator community must match those dreams with some of its own. Two special missions should be supported with an aggressive and massive Space Elevator Transportation Infrastructure. Mission I - Improving the human condition on Earth. Multiple projects can contribute towards this dream such as the delivery of 5 million tonnes of cargo to GEO, enabling the Space Solar Power architecture. Mission II - Living and working on off-planet colonies such as on Mars.

These dreams/missions are important as they lead to specific visions of what can be done and then become need statements for developmental projects. This process has worked several times for mega-projects and it shows that our dreams can lead to the development of Space Elevators. Dreamers make things happen as much by spreading the enthusiasm at each step along the way as any specific technology. What we need are dreamers who stimulate the rest of us to action.

2.2 Space Elevator Vision: As long range planners who have reveled in our opportunities to turn dreams into reality, we understand the need for a significant vision with positive impact on the future while maintaining a knowledge of engineering and programmatic reality. We hope we have earned the right to share our vision and express our beliefs in major space endeavors of significance. We believe:

- We are moving off-planet as a species as expressed by so many "big visions."
- Our (ISEC) vision is consistent with those dreams with a touch of reality: "*Space Elevators are the Green Road to Space as they enable humanity's most important missions by moving massive tonnage to GEO and beyond*." They accomplish this safely, routinely, inexpensively, and daily; while, being environmentally neutral.
- Our hope is that our Green Road to Space is a second lane in parallel with Blue Origin's vision of "building the road to space" for the next generation. We refer to this as Dual Space Access Architecture. Both roads are compatible and complementary as the architecture leverages the strengths of both future rockets and Space Elevators. Rockets will continue to play an integral part by opening up the pathways to the Moon and Mars, with Space Elevators being utilized to supply and grow these colonies. Space Elevators will provide the heavy lifting for off-planet expansion and enable “Green Missions” such as Space Solar Power and Sun Earth L-1 Solar Shade.

Since its creation in 2008 ISEC has: grown in participants, completed 12 study reports, held 15 yearly conferences in Seattle, and strengthened relationships with multiple organizations around the world such as the National Space Society, the International Academy of Astronautics and the British Interplanetary Society. Over the years we have been driven by our original vision: “A world with inexpensive, safe, routine, environmentally friendly, and efficient access to space for the benefit of all mankind.” As we have grown in scope and reach, our new vision goes beyond GEO to the Moon and Mars. In addition, having a strategic approach is important for bringing partners and investors into our plans. Space Elevators can support the full spectrum approach to off-planet and deep space exploration and colonization. Our new vision will match and support the remarkable visions emerging during this new decade of spaceflight.

> **NASA's Vision**: We reach for new heights and reveal the unknown for the benefit of humankind.
> **NASA”s Mission**: Drive advances in science, technology, aeronautics, and space exploration to enhance knowledge, education, innovation, economic vitality and stewardship of Earth.

Program for Off-Planet - Artemis: Boots on Moon 2024.

ESA Statement: "ESA Director General Jan Wörner and NASA Administrator Jim Bridenstine have signed a Memorandum of Understanding (MoU) to take Europe to the Moon." (ESA Announcement 28 Oct 2020).

National Space Society Vision; "People living and working in thriving communities beyond the Earth, and the use of the vast resources of space for the dramatic betterment of humanity."

SpaceX's Vision: "Making Humanity Multi-planetary,"

Blue Origin's Vision: "Millions of people living and working in space" and "I am going to build the road to space."

2.3 Demand Pull: This consolidation of customer needs leads to remarkable demands for logistical support of their missions. In addition, an analysis completed for the 2014 International Academy of Astronautics Study showed needs across the upcoming decades. This set of numbers compares well with currently expressed needs and visions. However, the bottom line is the demand pull from customers have expanded by orders of magnitude from the early 2000's. It is obvious to the authors that continuing with the conundrum of the rocket equation will not fulfill the dreams of many.

Table 1.1: Explanation of Demand Pull from Customers [Swan 2014]

Demand in Metric Tons	2031	2035	2040	2045
Space Solar Power	40,000	70,000	100,000	130,000
Nuclear Materials Disposal	12,000	18,000	24,000	30,000
Asteroid Mining	1,000	2,000	3,000	5,000
Interplanetary Flights	100	200	300	350
Innovative Missions to GEO	347	365	389	400
Colonization of Solar System	50	200	1,000	5,000
Marketing & Advertising	15	30	50	100
Sun Shades at L-1	5,000	10,000	5,000	3,000
Current GEO satellites + LEOs	347	365	389	400
Total Metric Tons per Year	58,859	101,160	134,128	174,250

In addition to a general summary, two missions stand out currently as needing Space Elevator's as their only realizable solution. They are Space Solar Power and Colonies off planet. These first few customer demands have been highlighted as they are current "big visions," each with large needs for delivery to space.

Table 1.2, Tonnage to Deliver

Vision	***Tonnage Required (tonnes to destination)***
Space Solar Power	5,000,000 tonnes to GEO [Mankins 2019]
Mars Colony	1,000,000 tonnes to Mars surface [Musk 2019]
L-5 Colony	11,000,000 tonnes to Earth Moon L-5 [O'Neill 1974]

2.3.1 Essential Support to Greening of the Earth - An Example, Space Solar Power: We all understand what that term means in today's pandemic world. I do not want to do anything but thank the "front line" participants of our war on COVID-19. But I see the space elevator players of today as especially critical at this time. We have an opportunity to make a difference while two forcing functions are in play:

1. Humanity is moving off-planet
2. The Space Elevator community has recognized that it can avoid the rocket equation AND assist in the "greening" of our planet.

Dr. John Mankins recently stated: " Space Solar Power can solve our energy and greenhouse gas emissions problems. Not just help, and just take a step in the right direction, but solve."[2]

As such, if we can contribute to the development of the Space Solar Power satellite constellation, we can "stop global warming." The beauty of this statement is that indeed, with our latest information about single crystal graphene (and other versions of 2D materials) we project to be operational by the last half of the next decade. Their complex and huge venture will not arrive at production until the middle of that decade; however, it seems reasonable that we can contribute significantly to the greening of the planet. There are three aspects that are being developed by our 2021 ISEC study group entitled "Beneficial Environmental Impacts from Space Elevators." The first is that the development of a massive transportation system has a very low impact on the environment. The second is that Space Elevator operations are carbon negative; and, the third is that Space Elevators will enable several global missions that will improve the planet's environment (SSP, Solar Shade, high-level nuclear waste diposal, and others). These three factors will be explained in detail upon completion of the research and publication of the study report (March 2021).

Leveraging Space Elevator capacity to move massive amounts of tonnage to GEO and beyond, without impacting the environment, will allow missions to exit the gravity well and ensures success. Can you imagine 5 million tonnes to GEO (Dr. Mankins' estimate - Oct 2019 at IAC in Washington DC) when launching 21 tonnes per event (Starship's launch to GEO with no refueling)? The principal strengths of Space Elevators are daily/routine movement to GEO and beyond with carbon negative operations. The latest ISEC study report shows that the mature architecture (six tethers in three Galactic Harbours) will move 170,000 tonnes per year. In perspective, that truly ENABLES Space Solar Power from GEO. Avoiding the gravity well, while being Earth friendly, and developing a transportation infrastructure will be critical to the Space Solar Power mission, and as such, to the betterment of the Earth's environment.

The next chart places all these discussions into perspective. Deriving information from the program documentation on the web and multiple papers (books, reports) leads to the following analyses and conclusions:

[2] Mankins, J. "The Case for Space Solar Power," Virginia Edition Publishing Co. Dec. 2013

- The middle line in the chart shows the projected needs from Space Solar Power for humanity across the globe which is estimated to be 1/8th of total need. This power would be coming from Space Solar Power constellation of satellites in GEO.
- This relates to the needs of Gigawatts (GW) delivered to the surface of the Earth. Using as an example of satellite systems, SPS Alpha Mk-II that is a front runner in the program plans for Space Solar Power, estimates can be developed. The mass to GEO and power delivered to the Earth's surface are estimated. Each Alpha Mk-II weighs approximately 10,000 tonnes to be delivered to GEO. Each Alpha Mk-II produces 2 GW of power to the surface of the Earth.
- One eighth of global needs for electrical power is estimated to be 727.8 GW (in 2068), leading to the demand from space to be 2 GW per MK-II or 364 systems or 3,640,000 tonnes delivered to GEO.
- If we use advanced rockets (using SpaceX's StarShip with 21 tonnes to GEO) we can show the delivery of mass to orbit by rockets. Mr. Musk has described three launches a day for his Mars missions, so we estimated the same to save the planet. That would result in 60 tonnes delivered to the GEO orbit per day x 365 or 21,900 tonnes per year. This process would take approximately 166 years. In fact, this is the bottom line in the next chart and shows that the customer's demand is never met.
- On the contrary, if one were to use the fully operational Space Elevator's vision of six fully operational capacity of 79 tonnes per tether per day, the delivery of mass matches the aggressive line in the chart fulfilling the customer's demand prior to 2070. This results from 170,000 tonnes delivered to GEO each year after 2050, or 17 SPS Alpha Mk-II satellite's mass delivered each year.
- If the customer desired one fourth of the energy demand from space, it would take a while longer. However, if it were deemed important enough to save our planet's environment, then more than 3 Galactic Harbours (6 tethers) could be in place by the middle of our current century and shorten the delivery time of mass to GEO.

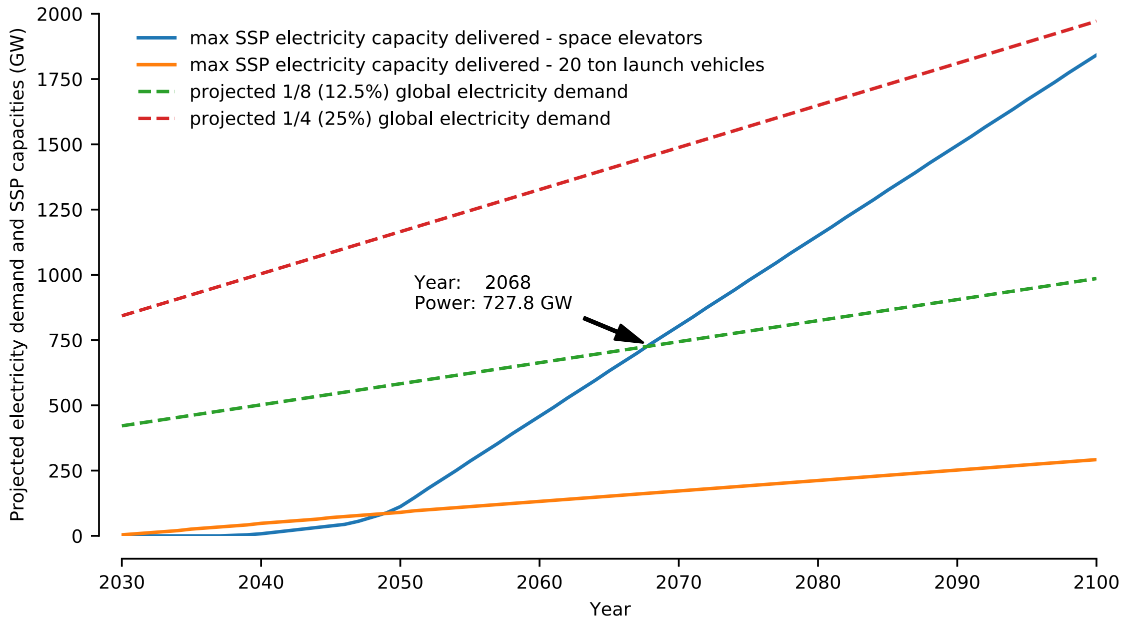


Figure 2.1, Satisfying Space Solar Power Tonnage to GEO

By evaluating the delivery dynamics of advanced rockets vs space elevators, the analysis shows that indeed space elevators can enable a climate saving technology in time to impact the health of the Earth. We've shown that with the full ISEC-proposed tonnage delivery capacity to GEO, it would be possible to deliver remarkable amounts of electrical power all over the world with SSP. Of course, it seems unlikely that the full capacity of the ISEC elevators would be used for a single client, but imagine if space elevator construction continued well beyond 6. Then such a schedule isn't so farfetched. We've also have shown that rockets will likely not be able to deliver SPS to GEO at volumes needed to reach 1/8 global electricity target. To do so would require in excess of 3000 launches a year to reach that target before 2100.

2.3.2 Off-Planet Colonies, L-5 and Mars: This discussion will show the concept of settlements from the viewpoint of how much mass is requested by the customer. There are two concepts that have been greatly discussed: Elon Musk's Mars Colony and Dr. O'Neill's [O'Neill1974] L-5 rotating cylinder colony. Here are a few descriptive sentences and then a recognition that they also need massive movement of cargo to fulfill their requirements.

Mr. Musk's Mars settlement has been discussed extensively ever since he first proposed a rocket design that could provide massive movement towards Mars. His design of the Starship vehicle has great hopes and it should be successful. In addition to suggesting that he will have a colony with upwards of a million settlers in place within his lifetime, he has stated that he requires 1,000,000 tonnes of cargo to support those on Mars. This customer need is straightforward. His images are well laid out and his understanding of the problem is excellent. As such, his Demand Pull for a transportation infrastructure is 1 million tonnes delivered during the decades of 2020 through 2060.

The original dream of the National Space Society (carried over from the original L-5 Society) is that they create a working and living space at the stable location trailing the Moon at an equivalent radius from the Earth. This L-5 orbital spot will provide a very suitable location for placing a million people inside a rotating structure. The dreams, visions, images and engineering designs have been around since the mid 1970s. However, the ability to deliver 11 million tons of supplies, infrastructure, power, water, oxygen and fuel was non-existent. As such, the dream has been "out there" but not fulfilled. Once again, an unsatisfied customer need.

Demand Pull is when a future customer needs something and asks developers to supply it. These two settlements have been dreamed of, and are now closer to fulfillment, for two reasons. The Human race has decided to move off planet making it a dream of many instead of a select few in space societies; and, the second is that the Space Elevator is very close to being developed - enabling the construction, supplying and staffing of the colonies. At 170,000 tonnes per year delivery to GEO and beyond, these customers can be satisfied.

2.4 Big Picture - Why Space Elevators?

2.4.1 Introduction: Others are ready to leap into the off-planet movement with future rockets while Space Elevators have tremendous strengths that have not been included in their strategy for going to the Moon and beyond. This movement off-planet must include Space Elevator architectures which provide the ability to:

- Depart the Apex Anchor at great velocity (7.76 km/sec)
- Support interplanetary missions (Fast Transit to Mars 61 days)
- Supply massive payloads (170,000 tonnes per year)

- Create entrepreneurial enterprises along the Galactic Harbour
- Enable new environmentally significant missions (Space Solar Power, Solar Shades, hi-level nuclear waste disposal, etc.)
- Enable carbon negative operations for delivery to orbit
- Exit the gravity well and avoid the burden of the rocket equation
- Accomplish all this daily, routinely, inexpensively and carbon neutrally.

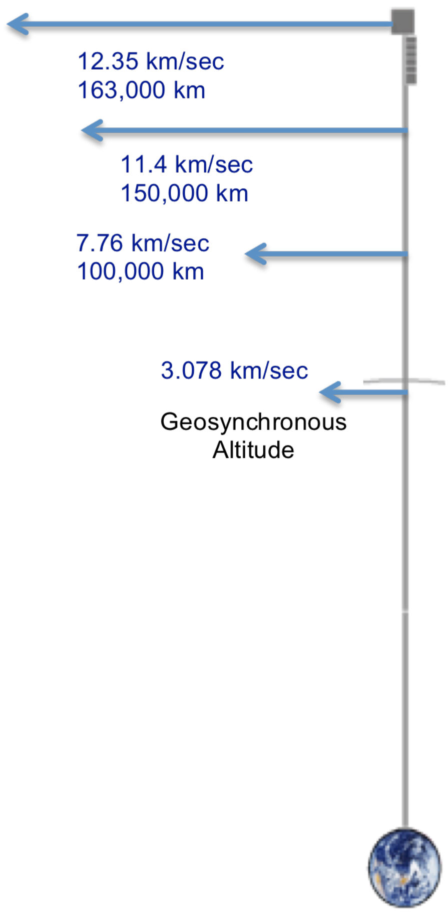
This series of needs can be accomplished if the Space Elevator program is initiated in the very near future.

2.4.2 Strengths of Space Elevators: Essentially, we see the strengths as infrastructures that lead to daily, routine, environmentally friendly and inexpensive departures towards mission destinations. This inherent capability results from the "permanent" characteristics of a road into outer space. Once a Space Elevator has been installed and upgraded to its initial capability, it will be there for a very long time, similar to roads, bridges and train tracks. Raising a payload from the surface of the ocean to the Apex Anchor (100,000 km as a starting concept) is accomplished with external power - such as solar energy, not the consumption of fossil fuels. This environmentally friendly approach is significant in its expectation of fulfilling the dreams of many.

Basic Strengths: In addition to a permanent infrastructure's core strength, the dynamics of space elevators enable delivery to optimum locations for satellites. One such location matches the historic geosynchronous altitude around the Earth. These orbital slots are valuable for missions such as space solar power and communications satellites. This region will grow as more and more capability is installed using Space Elevators -- resulting in high potential for supporting entrepreneurs. Missions such as spacecraft repair and/or refueling and assembly of larger spacecraft will expand rapidly once this low cost of delivery is developed. Because of their characteristics, Space Elevators deliver payloads to their intended destination without consumption of mass. Essentially, at the Earth Port, the payload is about 70% of the mass and will be raised to its release destination without consuming anything. The tether climber remains intact as it is energized from external sources (the Sun) and is then reused once it completes its mission(s). In addition, the use of Space Elevators ensures that space missions can be initiated without endangering the Earth or its environment.

There will be no rocket exhaust reacting inside the atmosphere nor rocket bodies cluttering up low Earth orbits. A permanent infrastructure which raises tether climbers using electricity is inherently Earth friendly.

Figure 2.2, Release Velocities



Release Geometries
(Credit: ISEC)

Surprising Interplanetary Strengths:
Conclusions from our ASU study showed that multiple strengths emerged which have not yet been developed. They showed that the design of Space Elevators lends itself to interplanetary missions as it transfers tremendous amounts of energy at release. A 100,000 km Apex Anchor can release towards the Moon and Mars with an amazing inherent velocity; and, of course, it has huge potential energy due to altitude. The velocity at release from the Apex Anchor is approximately 7.76 km/sec towards mission destinations allowing:

- Fast transit to planets (Can you imagine -- as fast as 61 days to Mars with average flight times in the 80 to 120 day region?).
- Daily releases of mission cargo towards Mars and/or other interplanetary locations. (Imagine no 26 month wait for a launch window!) In addition, the study showed that with longer tethers, the release velocity increases to enable Solar System escape.
- Massive tonnage of cargo towards mission destinations -- 5,000 tonnes for the first space elevator releases growing to 170,000 tonnes per year for a six space elevator mature infrastructure.

Two Recent Strengths: In addition to all the above benefits, two more have surfaced in the last two ISEC study reports:

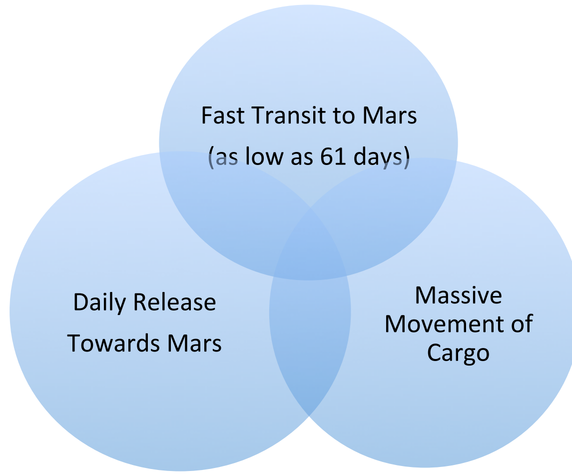


Figure 2.3, Interplanetary

- Reduction in Environmental Impact: As the tether climber ascends the Space Elevator, it receives energy from the sun and does not pollute to escape from the gravity well. The reduction of rocket launches to only critical ones will reduce their atmospheric impacts, hazardous production, low Earth orbit debris, and pollution around launch sites, while virtually elimination of payload loss/damage through shake, rattle and roll of rocket launches or possible explosions.
- Promise to Planetary Scientists: Planetary scientific instruments, and their support equipment, can be assembled at the Apex Anchor with no restrictions of mass. In addition, daily releases can be achieved towards all planets or asteroids at high velocity.

2.4.3 Summary of "Big Picture", Why? As long range planners who has reveled in opportunities to turn dreams into reality, we understand the need for a significant vision with positive impact on the future while maintaining a sprinkling of engineering and programmatic reality. We believe:

- Space Elevators will move tonnage rapidly, safely, inexpensively, environmentally friendly, and in large numbers to multiple destinations as a Green Road to Space, thus enabling so many dreams and needs of humanity.
- We are moving off-planet as a species as expressed in the many "big visions."
- Our (ISEC) vision is consistent with those dreams with a touch of reality. Space Elevators accomplish this safely, routinely, inexpensively, and daily; while they are environmentally neutral.

- Our hope and belief is that our road to space is a second lane in parallel with Blue Origin's vision of "building the road to space" for the next generation. We refer to this as a Dual Space Access Architecture. Both roads are compatible and complementary as the architecture leverages the strengths of both future rockets and Space Elevators.

2.5 New Space Elevator Vision: In response to these tremendous demands for mass delivered off-planet, a new vision was necessary.

Space Elevators are the Green Road to Space while they enable humanity's most important missions by moving massive tonnage to GEO and beyond. They accomplish this safely, routinely, inexpensively, and daily; while, they are environmentally neutral.

Chapter Three Dual Space Access Architecture

3.0 Reaching Orbit: When we look at the Moon and dream of spaceflight, we forget how extremely difficult it was to accomplish, both in energy and design complexity. Tsiolkovsky's remarkable rocket equation consumes so much mass to achieve orbit that, historically, we have been restricted as to what we can deliver. Now that we have decided to go to the Moon and on to Mars in a combined international, governmental and commercial efforts of great magnitude, we need to expand our vision of 'how to.' It would seem that the establishment of a more robust infrastructure with reusable rockets and permanent Space Elevators must be developed. In this chapter, we discuss the strengths and weaknesses of the components of this combined architecture with the purpose of placing mission equipment and people where they need to go and when they need to be there. The multiple destinations, complexity of orbits, magnitude of each transition to orbit, and infrequent launches currently means that the difficulty of fulfilling the dreams of the many is a monumental "reach." Expanding space access architectures to include Space Elevators will enable a robust movement off-planet. This robust infrastructure enables the National Space Society's Mission:

> "The National Space Society (NSS) is an independent, nonpartisan, educational, grassroots, non-profit organization dedicated to the creation of a spacefaring civilization."

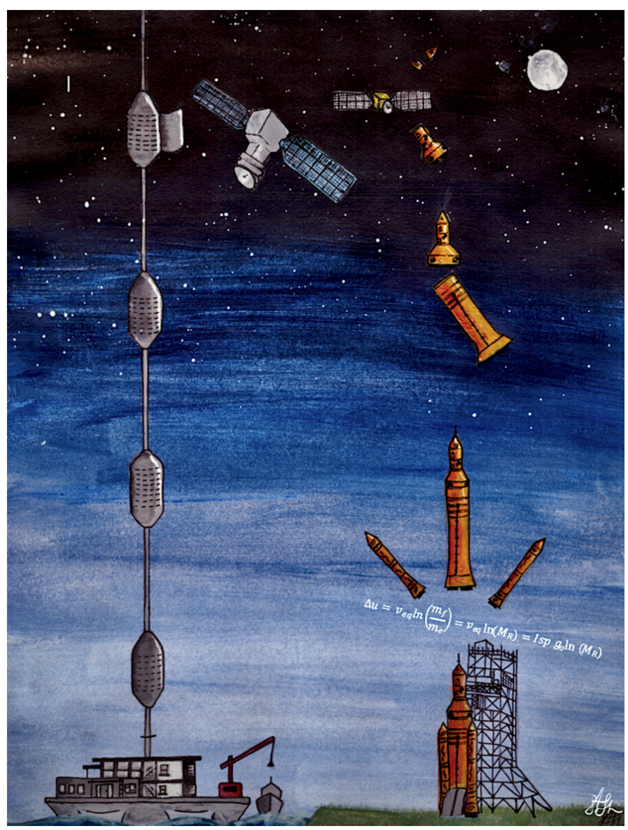


Figure 3.1, Dual Space Access Architecture Amelia Stanton Image

During the discussions for this chapter we reached across the strengths of rocket launches along with their difficulties. We recognize that there are three principal strengths: 1) rockets are successful today and great strides are forecast for the future, 2) reaching any orbit can be achieved, and, 3) rapid movement through radiation belts for people enables flights to the Moon and Mars. I will also point out the strengths of a permanent infrastructure with daily, routine, environmentally friendly and inexpensive attributes. These Space Elevator strengths are compared to the difficulties of executing a Space Elevator developmental program. Space Elevators will not be ready for the initial human migration off-planet. However, once colonies are established on the Moon and Mars using rockets, Space Elevators will enable their robust growth.

3.1 Multiple Infrastructures in Parallel: The concept of a Dual Space Access Architecture is simple. We must leverage both advanced rockets and Space Elevators.

> ***Rockets** will continue to play an integral part by opening up pathways to the Moon and Mars, with Space Elevators being utilized to supply and grow the colonies.*
> ***Space Elevators** will provide the heavy lifting for off-planet expansion and enable "Green Missions" such as Space Solar Power and Sun Earth L-1 Solar Shade. This compatible and complementary approach leverages the strengths of both future rockets and Space Elevators.*

Our hopes for movement off-planet are rising as we listen to visionaries such as Jim Bridenstine, Jeff Bezos and Elon Musk with their massive rockets designed to carry amazing loads to orbit. Who could have imagined, just five years ago, that a company could launch a preliminary version of a StarShip rocket able to take 100 people and 100 metric tonnes to Mars? Who would have imagined just three years ago that there would be a "Blue Moon" lander competing commercially to place people on the surface of the Moon near the south pole with its frozen water supplies? Who would have believed that NASA's goal would be for a 2024 landing on the Moon with astronauts of both genders?

But hold on - these visionaries have been matched with Space Elevator innovators showing a future capability to go to geosynchronous and beyond with electricity -- thus defeating the rocket equation that demands the consumption of huge masses. Space Elevators are closer than you think; and, they are ready for major segment engineering development leading to validation testing. The concept is so enticing that it allows us to envision a mature Space Elevator infrastructure with six tethers able to release over 170,000 tonnes per year towards the Moon and Mars (as well as placing satellites at the GEO altitude).

The essence of this report is that the two methods of achieving spaceflight are complementary and compatible rather than competitive. Each has their own strengths and weaknesses. Future rockets are being designed now to deliver payloads to the Moon in the near term (2023 +). Next comes their growth to massive launches, in both number and payloads, occurring in the second half of this decade with the 30's having mature rocket architectures. Development on the Moon, and an initial colony on Mars, will be well along by the early 30's. By the end of that decade, Space Elevator infrastructures will be incrementally built with more and more capability leading to the enabling of many complementary missions. Our vision towards the turn of that decade is that there will be six Space Elevators located around the equator helping with the delivery of massive amounts of payloads to GEO, the Moon, and Mars. Our concept will have daily departures to each, rapid travel to each (as fast as 61 days to Mars), and with massive amounts of payload to support people at multiple destinations. A good way to express the team arrangement could be:

Rockets to Open up the Moon and Mars with
Space Elevators to supply and grow the colonies.

3.2 Beauty of Rockets: This historic approach of reaching orbit with rockets has led to remarkable missions. The comfort level is high and the ability to repeat is well known. Customers demand that their satellites be placed in specific orbits in order to fulfill their mission needs - from low Earth orbit with high inclinations to unique constellations of satellites for communications. Medium Earth orbits require more energy and specific location insertions to ensure that navigation signals are able to span the globe. These unique orbits require specific timing (launch windows) and insertion vectors to match orbital characteristics. Rockets are very good at fulfilling a variety of customer requests -- about 100 times per year. Multiple launches per year by each separate launch vehicle is becoming routine; but matching launch location and mission orbits requires serious planning and execution. As one who lived through the marvelous development of human spaceflight, this capability to move humans with rockets is an exciting strength. Trips to the Moon highlighted the commitment of moving off planet with remarkable flights pushing the envelope of risk and achievements. The fast transition through radiation is a major strength of rockets and ensures that astronauts' exposure is minimized. In the future, rapid transit through the Van Allen Belts will continue to be a strength of rockets inside a Compatible Architecture. Another series of strengths arise from the need to apply desired forces using small rockets integrated within spacecraft. These propulsion devices accomplish so many parts of the missions: Spacecraft pointing, stabilizing a spinning spacecraft, transition between orbits (departure and then matching), interplanetary insertion with correction burns, rendezvous with other satellites or locations in orbit, deceleration into orbits around planets or moons, landing on planetary surfaces, and launching from planetary surfaces. As one who helped design spacecraft, I always marveled at these little rockets "that could."

3.3 Beauty of Space Elevators: The future of humanity's travel within our solar system requires permanent space infrastructures that provide access to space with the following strengths:

- Routine [daily],
- Revolutionarily inexpensive [<$100 per kg]
- Commercial development similar to bridge building
- Permanent infrastructure [24/7/365/50 years]
- Environmentally sound
- Safe and reliable [no shake, rattle and roll]
- Low risk lifting
- Low probability of creating orbital debris
- Redundant paths as multiple sets of space elevators become operational
- Massive loads per day [starts at 20 metric tonnes]
- Opens up tremendous design opportunities for users
- Optimized for geostationary orbits and beyond.

There will be no rocket exhaust into the atmosphere nor rocket bodies cluttering up low Earth orbits. We recognize that a permanent infrastructure which raises tether climbers using electricity is inherently Earth friendly. Space Elevators are really the Green Road to space.

3.4 Massive Tonnage Enables Earth Improving Missions: ISEC has started a year-long study to assess the environmental benefits of leveraging Space Elevators in a combined architecture. By providing massive movement to GEO, Space Elevators will enable missions that will improve conditions on Earth. The specific currently envisioned mission that would greatly benefit humanity is Space Solar Power for supplying energy from the sun continuously and cheaply. This radiated energy approach can ensure delivery any place on the globe and eliminate hundreds of coal burning plants (this NSS endorsed mission supplies electricity for 12% of Earth's population in 2060). The need has been described as requiring five million metric tonnes to geosynchronous orbit. Even at full capacity, the Space Elevator architecture would take over 20 years during their development to fulfill this customer's needs. A strength of Space Elevators is that they can provide this quantity of mass to GEO without impacting the atmosphere. This tasking is virtually impossible with a rockets only approach. There are many other missions not recognized as "doable" today because of the lack of liftoff capability for bold missions to help the Earth and humanity. These would include Sun-Earth L-1 Solar Shade to reduce energy hitting the Earth and the capability to permanently deliver high level nuclear waste to low Solar orbit, never to approach Earth again.

3.5 Combined Architecture - Overlapping Strengths Reduce Shortfalls: The strengths of this Dual Space Access Architecture enables human migration off-planet robustly and safely. Space delivery can become as routine as Fed-Ex, Amazon, and DHL are today. One significant conclusion is that using the strengths of this combined Architecture enables so much more than their individual parts. Customers must also take into account the short-falls of each major segment of the Architecture.

3.5.1 Rocket Architecture Short-falls: As I see it in 2021, rocket systems are working towards many improvements that will have significant impacts. The reusability of major segments will lower the cost while making the rockets massive will enable bigger payloads. However, the major flaw of the rocket approach is the consumption of its initial mass at the pad to reach the velocity required for flight. This consumption of pad mass is a huge portion of the total vehicle weight and decreases the payload capability for each launch. Essentially, to reach LEO, the rocket equation consumes 96% of pad mass (fuel burned and structure used). The remaining 4% is the payload mission equipment, with everything else released earlier for reuse, left in lower orbits as debris, or burned up to gain velocity. The reality is that 17,000 miles an hour to stay in LEO is demanding. To gain enough velocity to go to the Moon, GEO, or Mars, the rocket equation demands consumption of more fuel, structure, electronics and equipment along the way. The final velocity is hard to reach and those other parts of the rocket do not contribute to the next stage of the mission; and so, they are "thrown-away" while consuming fuel. Only two percent of the original launch mass is sent towards high orbits enabling their escape from gravity. The real catastrophic number illustrating this point was the Apollo equipment that landed on the Moon (with Astronauts) represented less than half a percent of the mass on the launch pad at Cape Canaveral. Consuming fuel, structure and equipment to gain velocity is a brutal approach - of course, it is the only approach today; but, it is still brutal. There are no "cost" or "reusability" factors in the rocket equation. You can do it more efficiently, but you can not beat the 124 year old equation. More launches and reusability of segments, the price is coming down significantly. Commercial companies such as SpaceX are approaching more than 50 launches per year and planning for hundreds of launches per year.

Table 3.1, Launch to Destination Mass

Launch Vehicle	***Mass on Pad (kg)***	***Mass Delivery***	***%***
Apollo Saturn V	3,233,256	Lunar lander = 15,103	0.5
		ocean landing = 5,557	0.17
Atlas V	590,000	to GEO = 8,700	1.4
Falcon Heavy	1,420,788	to GEO = 26,700	1.9
Starship	4,000,000	to GEO = 21000	0.5
New Glenn	1,323,529	to GEO = 13,000	1

Once again, the question becomes:

> *Should humanity depend upon a transportation infrastructure that delivers only 4% (to LEO), 2% (to GEO), or 0.5% (to Lunar surface) of its original mass to its destination?*

The question: How many tonnes have been delivered to orbit between 1957 and 2020, and how does that impact future dreams of colonies, Space Solar Power or exploration? After spending hours searching for a single data point, I was forced to summarize, estimate and add the numbers across a diverse set of data towards a total. The answer (within 5% probably) is the total mass to orbit is approximately 22,216 tonnes.

Table 3.2, Breakout of History Mass to Orbit

Type of Systems	***Orbit***	***Mass***	***Mass on pad***
		Tonnes	tonnes
Space Stations	LEO	431	10775
Earth Orbiting Sat's 2020	LEO, MEO, GEO	3220	80500
past satellites deorbited	LEO, MEO, GEO	1000	25000
Interplanetary	Solar System	100	5000
Lunar spacecraft	to the Moon	94	4700
Human to LEO	LEO	535	13375
Apollo Capsule to Moon	Lunar	336	16800
Space Shuttle*	LEO	16500	412500
Totals		22,216	568,650

Note: Leo is 4% of launch pad mass
GEO, Interplanetary, Lunar 2% of pad
*Shuttle launch vehicle reached orbit as an operational satellite

Result: 22,216 tonnes between 1957 and 2020.

The future is looking bright for big rockets that are reusable and less expensive. There will be more and more mass placed into orbit. In addition, I estimated the total mass at the launch pad by using (roughly) 4% of the launch pad mass reached LEO as payload and 2% reached GEO/Lunar/Solar System. This resulted in over a half million tonnes (568,650) at the launch pad before the rocket was ignited and the payloads fought their way out of the gravity well.

3.5.2 Space Elevator Short-falls: We realize that a basic concern about Space Elevators is that they will not be ready for humanity's initial migration off-planet. Dates such as 2024 or 2030 are prior to even the first Space Elevator. In addition, one of the biggest shortfalls of Space Elevators is that they are not really designed to support Low Earth Orbit (and poor at Medium Earth Orbit). A Space Elevator can provide spacecraft into LEO and MEO orbits, just not very efficiently. A third concern for Space Elevator permanent infrastructure development is that it will take time to construct and ramp up. Current estimates are Initial Operational Capability (20 tonne climber capability) will be somewhere after 2032 with Full

Operational Capability (100 tonne climber) around 2045. Development of permanent infrastructures around the equator will not be quick; however, their operations will enable releases towards mission destinations without consuming fuel or rocket structures.

3.6 Vision of the Future: On to Mars: If the Mars access strategy has two components, you end up with a much stronger position having both rocket architectures of the future and permanent Space Elevator infrastructures supporting movement off-planet. Assessing the previous discussions showing strengths and weaknesses, the logical conclusion is that there should be a concerted effort to ensure development towards a combined Space Access Architecture. Some basic realizations are that: (1) rockets should be emphasized for movement of people, (2) rockets have tremendous strengths for LEO/MEO destinations, (3) Space Elevators should be leveraged for GEO and beyond, and (4) Space Elevators should be used to deliver cargo, equipment, and supplies for Lunar and interplanetary missions. These factors lead to the realization that developmental planning must be initiated in the very near future for both advanced rockets and Space Elevators. As one who was involved in the interplanetary study by ASU and ISEC, I recognize the strengths and weaknesses of both architectures, resulting in:

"Dual Space Access Architecture"
Rockets to Open up the Moon and Mars
with Space Elevators to supply and grow the colonies.

Chapter Four Near Term Destination and Growth Pattern

4.0 Destination: The concept of a Galactic Harbour defines where we are going and how we will support our customers. Preliminary architectures for Space Elevator development are laid out in many places with ISEC focusing upon the Galactic Harbour concept. For the purpose of this discussion, a Space Elevator is a transportation infrastructure leveraging the rotation of the Earth to raise payloads from the Earth's surface towards space and our solar system. It is a part of the global transportation infrastructure.

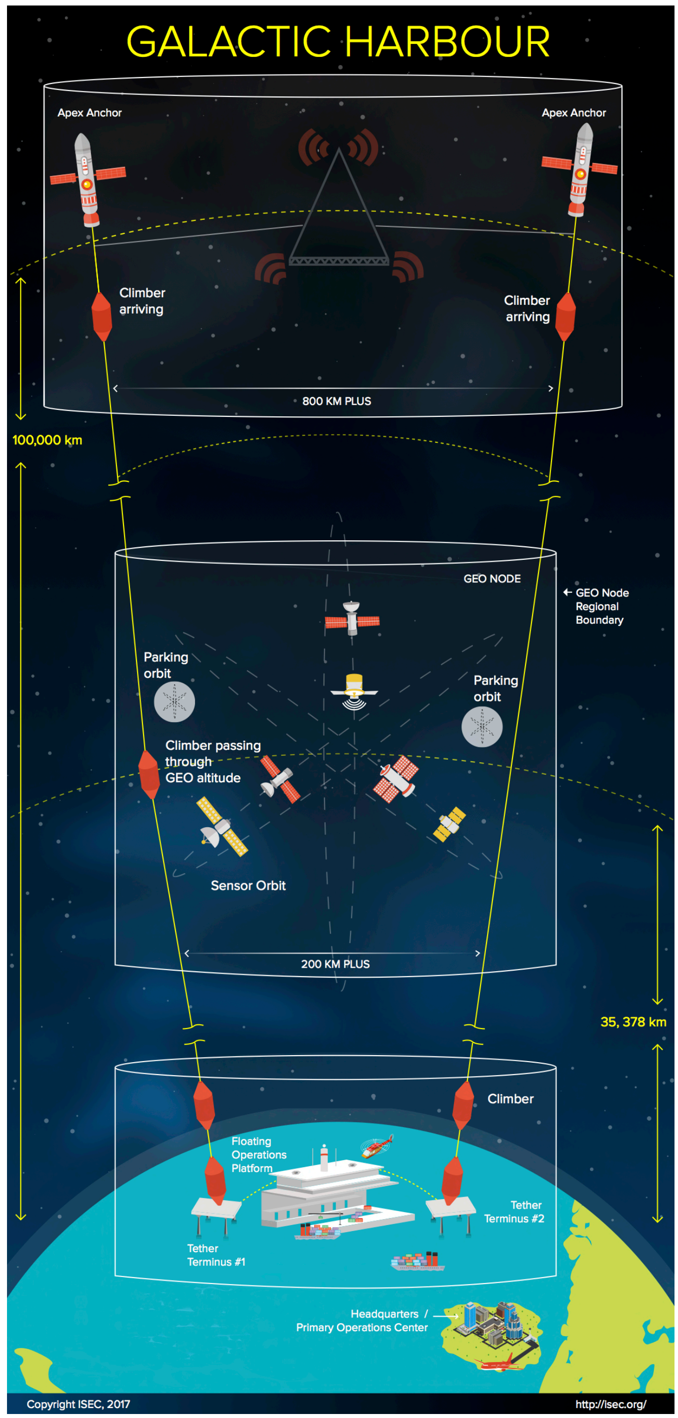


Figure 4.1, Galactic Harbour

In a mature environment where Space Elevators are thriving in business and commerce, there would be several (probably up to ten) spread around the equator, each with a capability of lifting off greater than 20 metric tons of payload per day, routinely and inexpensively. The Galactic Harbour is the area encompassing the Earth Port [covering the ocean where incoming and outgoing ships/helicopters and airplanes operate] and stretches up in a cylindrical shape to include tethers and other assets outwards towards Apex Anchors. In summary, customer product/payloads [satellites, resources, etc.] will enter the Galactic Harbour around the Earth Port and exit somewhere up the tether [to LEO, GEO regions, Mars, Moon, asteroids, intergalactic, and towards the sun, depending upon where it is released].

Galactic Harbours will Unify Transportation and Enterprise Throughout the Regions.

4.1 Space Elevator Transportation System – Concept Baseline:[3] The Space Elevator Transportation System is the core of our vision. This is what ISEC is declaring is ready to enter Engineering Validation. It is the transportation system that will provide affordable and reliable access to space. This transportation system has six segments. The Earth Port, Apex Anchor, GEO Region, Climber, Tether, and Headquarters / Principle Operating Center (HQ/POC). The HQ/POC is embedded in the Earth Port and has an expansion element on nearby land; in its Access City. Each of these six pieces must be described in explicit and finite terms with ascribed engineering performance based upon detailed "show me" efforts to be conducted in Phase 2 of the ISEC Development Plan: How strong the Tether, how fast the Climber, how mobile the Earth Port, and how aware the HQ/POC; and more. Baseline building is a hit and miss iterative process -- a bootstrap miracle. Baselines are built by trial and error mixed with sweat and tears. ISEC expects to publish the FIRST Engineering validated baseline by the middle of Phase #2. This Space Elevator baseline is shown as the sum of the parts, as of the Spring of 2021:

1. One Earth Port Floating Operations Platform, Two Tether Termini, and one Access City
2. One GEO Region provides support to a range of space based enterprises: Space Solar Power collection, Space Based factories, satellite repair and satellite refueling.
3. One Apex Anchor, interplanetary departure support,
4. One HQ/POC, a major portion collocated at the Earth Port FOP, a substantial portion of the HQ/POC
5. Two Tethers
6. 14 operating tether climbers.

[3] Fitzgerald, M. Swan, P. "The Technical Maturity and Development Readiness of the Galactic Harbour," IAC-19-D4.3.2, Washington DC.

In addition, there are three adjunct elements to the basic architecture. They are:

1. Space Debris (Mitigation) -- Space Elevators will establish a close operational relationship with space debris mitigation systems that will be operating near Earth within the next decade. The space debris "chair" will be a permanent member of the HQ/POC and be charged with supporting or providing awareness, warning, active defense, passive defense, and (if needed) recovery after a debris event.
2. Space and Surface Object (Situational Awareness)
3. Client Support and Management

4.2 Growth Pattern: Our current vision shows the growth from an initial Space Elevator with the addition of a backup creating a two Space Elevator Galactic Harbour - then competition drives two more Galactic Harbours in the near term around the equator. This results in out year throughputs of somewhere around 170,000 tonnes per year, as compared to the total tonnage to orbit from 1957 through 2020 of only 22,000 tonnes.

Fifty plus years after the Apollo missions, humans have decided to create a permanent presence in space, on the Moon, and Mars. Our strategic approach and vision is in line with the original statement in this paper. This vision includes three Galactic Harbours, with two Space Elevators each, leading to a carbon neutral delivery of a minimum of 170,000 tonnes to GEO and beyond by 2040.

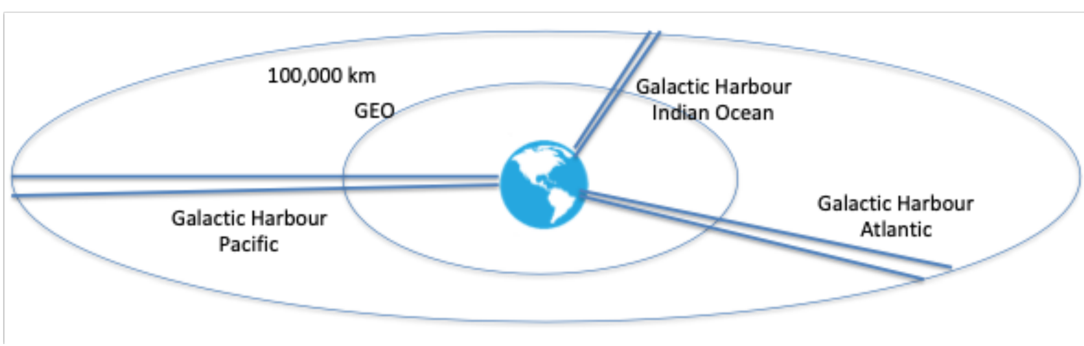


Figure 4.2, Future Architecture, 3 GHs

Two designs have matured over the last 17 years show the Initial Operating Capability could be around 14 tonnes to GEO and beyond per day. Once Galactic Harbours mature towards the Obayashi Corporation's design

(Obayashi 2014) the daily capability goes up to 79 tonnes. We call this maturation of cargo tonnage, the Full Operational Capability. Doing the math, there would be 5,110 tonnes to GEO and beyond per year initially with growth towards 28,835 tonnes per year per Space Elevator. Of course this architecture matures not only in tonnage throughput, but also number of Space Elevators from both competition and demand pull (customer needs). The current concept is for the initial operational capability to be 14 tonnes per tether climber once a day or 30,660 tonnes per year somewhere in the 2032 time period. Future improvement of the architecture will lead to the full operational capability of 79 tonnes per day or 173,010 tonnes per year by 2045.

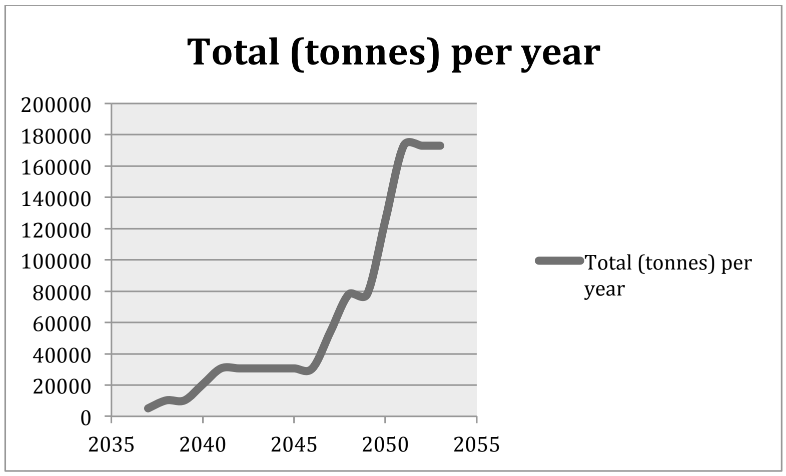


Figure 4.3 , Throughput

These numbers reflect the characteristics of a transportation infrastructure instead of one-time events. The following growth pattern seems logical and leads to our vision. Once the Space Elevator concept program reaches initial operations capability, its growth will be similar to all previous transportation infrastructures -- something like:

- Step One: The initial operations capable tether starts daily commercial operations - single tether, 14 tonnes to GEO and beyond.
- Step Two: Immediately finishes second tether inside first Galactic Harbour - two tethers, 14 tonnes each. This ensures each Galactic Harbour maintains operations with a backup. In addition, humanity will never be trapped by gravity again.
- Step Three: Graduated growth in the number of Galactic Harbours occurs with three spread around the equator seems reasonable from a competitive perspective (commercial and government level). Each has two tethers, 14 tonnes daily each.

- Step Four: Each tether grows in capability towards Full Operational Capacity of 79 tonnes per day. Each Galactic Harbour grows until they each have two 79 tonne capability tethers.

4.3 Expansion of Global Intermodalism towards third dimension - space (much of this section was borrowed from "Earth Port Access City: The Case for Honolulu, Hi"[4]:

This discussion explains how the Space Elevator will be adding a third dimension to the well developed and essentially two dimensional global transportation chain of ports, harbors, commercial aircraft and cargo carrying marine vessels. In doing so, the concept of an Earth Port is described as a basic element of the Space Elevator infrastructure. The basic elements of today's global cargo transportation system include: ocean going ships, railroads, trucks and cargo planes. As a generalization, the most cost effective way of transporting large quantities of cargo over long distances has been, and will continue to be, by ocean going vessel. On the other hand, small quantities of time sensitive, high value cargo are typically transported by commercial airlines. In the 1970's the concept of international standard shipping container became a reality and has developed in the ensuing years as the primary mode of moving cargo around the globe. Containerization led to intermodalism.

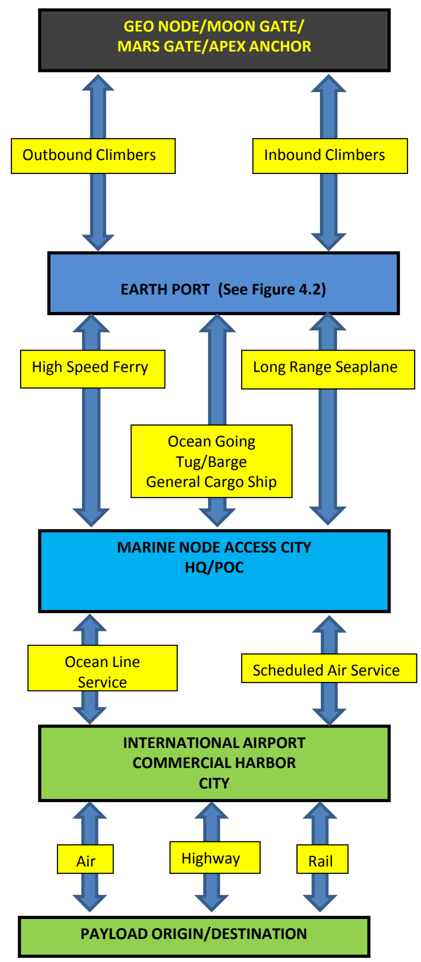


Figure 4.4, Transportation Paths

Under this now common system, a product can be secured inside a container at its origin, then trucked to a regional seaport, placed aboard a container ship (along with thousands of others), shipped across an ocean to another seaport, placed upon a specialized "unit" train, transported across country to a distribution center in a regional city and finally removed from the original

4 Hall, Vern, "Earth Port Access City: The Case for Honolulu, Hi," ISEC Conference, 2017.

container and placed onto a local truck taking it to its ultimate destination or market. The various entities and businesses involved in this transportation system form what is known as the global logistics supply chain. These entities include: shipping lines (ship owners), seaport and rail terminal operators (e.g. stevedoring firms), railroad owners and operators, government customs officials, customs agents, freight forwarders, trucking companies, labor unions, public port authorities, etc. In the transportation industry there is a large body of technical knowledge that is commonly called supply chain management. This body of knowledge is becoming increasingly sophisticated by using advances in computer and communications technologies. As an example, it was recently announced that the world's largest shipping line, Maersk, is working with IBM to develop and use so-called blockchain technology5 to keep track of shipments from source to destination. Not just the containers themselves, but their contents. This ability to continuously track cargo is aided by another emerging technology called the Internet of Things, ("IoT") that relies on remote sensing technology and digital interconnectivity on a global scale.

With all its complexity and world-wide scope, today's transportation system is basically two-dimensional. The movement of cargo and people is either by land, on the water or by air, well within the earth's atmosphere, or by some combination thereof. But how do we get stuff into space? It's moved to a rocket launch facility somewhere on land or on the ocean using the existing transportation system, then shot into space using conventional government owned or private booster rockets. Even today, each lift off and return are not routine; they are events. The Space Elevator, once IOC6 (and beyond) is achieved, will definitely add the third dimension to the global transportation system. We can call it the Z-axis, up and down. Using the Space Elevator, payloads can be moved to/from orbit and/or space in a safe, reliable and routine manner. The operation of the Space Elevator, both as a new transportation infrastructure and a business enterprise must seamlessly mesh with the existing and future global transportation system. The physical point where this meshing of systems should occur logically would be at the HQ/POC facilities located at or near the Earth Port Access City.

4.4 Dual Space Access Architecture Example - Going with Mr. Musk to Mars:

The following discussion baselines SpaceX's Starship

[5] For a cursory description of blockchain technology, please see ISEC Newsletter Earth Port update #5, April 2017

[6] IOC: Initial Operational Capability as described in various ISEC publications

Approach to Open up a Mars Colony[7]. Mr. Musk's desires are to have his colony of over 1,000,000 people on Mars during his lifetime (so let's give it 40 more years from 2020). In addition, he has stated that he needs one million tonnes delivered to Mars to support his developing colony. One of the first planning thoughts must be that the window to launch towards Mars from Earth, via a Starship, is only an 8-week window every 26-months. Once he has established the process for colonization and initiated the Colony with explorers and early settlers, SpaceX envisions loading the 1,000 Starships during the periodic 26-month window. Then all 1,000 (carrying approximately 100,000 passengers with 100 tonnes of cargo each) would then embark on the 40-400 (Avg of 150) day transit to Mars. The 1,000 Starships would land on the surface of Mars for unloading and then loading for the return trip to Earth. For the return trip, an extended time period also applies [McFall-Johnson 2020]. Therefore, for a complete round trip to Mars and back would take approximately 5years. At this pace, it would take 50 years to transport 1-million people to Mars. However, a smaller goal of only 100,000 would take only 5 years to transport the people to Mars. [Musk 2017] Currently, each individual SpaceX Mars mission transport spacecraft would include: logistics support launches such as: one passenger rocket with mission Starship (100 people), three fuel rockets, and one cargo rocket. One Mars Starship mission equates to 5 operational rocket launches from Earth.

[7] This explanation is Dr. Swan's approach to understand SpaceX's approach: It is probably "off" target in a few points, but it is used as an example for understanding the Dual Space Access Concept.

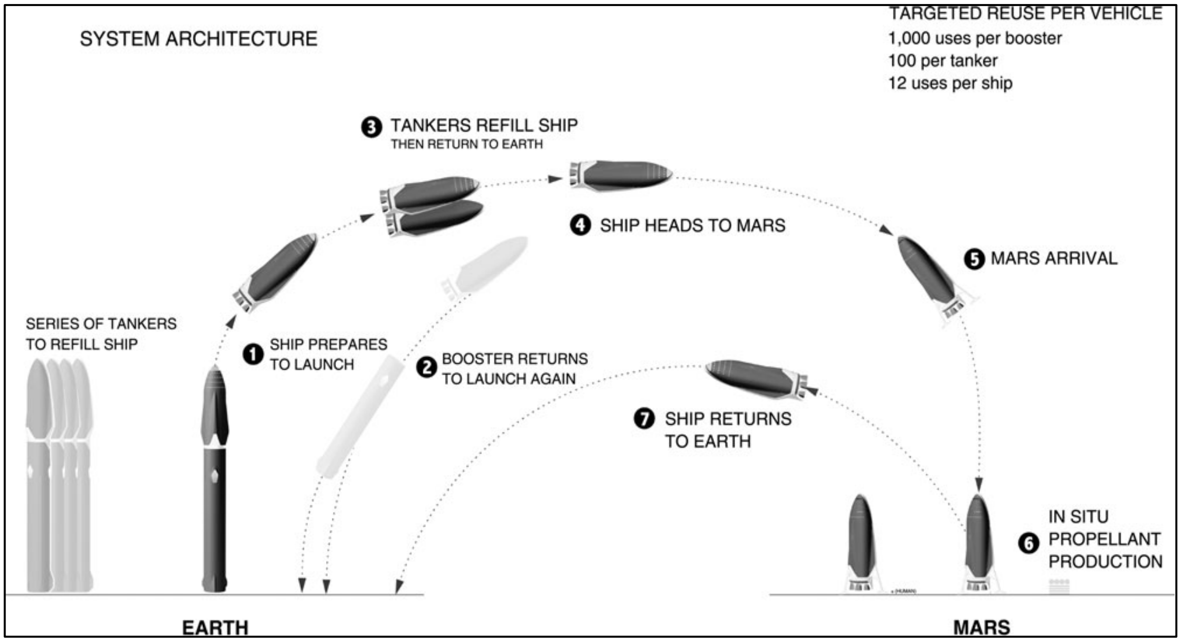


Figure 4.5, System Architecture of Starship To/From Mars [SpaceX]

The new few points illustrate the operational concept of using Space X's Starship (Notes from SpaceX's website):

1) A series of tankers would be ready to refill the mission Starship. They would be launched into LEO to refill the Starship and then return to Earth for refilling. It is envisioned that the propellant tanker would go up anywhere from three to five times to fill the tanks of the Starship in orbit. In addition, there is the logistics supply ship to supply for the trip to Mars.

2) Mission Starships would launch from prescribed launching pads on Earth with payloads (people, materials) and would be fueled in LEO by the tankers.

3) Once fueled, there would be 1,000 Starships making the journey to Mars every 26-months. This way the Mars fleet would depart in masse to Mars over an 8 week period (or an average of 18 trans-Mars injections per day.

4) Once arriving at the destination, the rocket would land on the surface to unload.

5) Once refurbished, refueled, and reloaded, the rocket would make the return trip to Earth. (NOTE: Propellant would be loaded on Mars for the return trip after being produced from the atmosphere and in situ resources).

6) The rocket would land on the Earth to unload and be refurbished.

7) Repeat steps 1 – 6 as required.

To simplify these numbers, if the number is one million people with one ton per person, the common factor would be a mission Starship's capability to deliver to Mars 100 people and 100 tonnes. If those assumptions are a good starting point, then it would take 10,000 mission Starships to deliver the stated quantity of payload and passengers. As explained, the need for five launches for each mission Starship to depart for Mars, that would be approximately 50,000 launches. Mr. Musk has also stated his objective to be able to launch three times a day. Without factoring in the clustering necessary to match launch windows with Mars, the total number of years for those 50,000 launches would be: 16,667 days or 45.6 years.

Assessing the previous discussions showing strengths and weaknesses, the logical conclusion is that there should be a concerted effort to ensure development towards a combined Space Access Architecture. Some basic realizations are that: (1) rockets should be emphasized for people movement, (2) rockets have tremendous strengths for LEO/MEO destinations, (3) Space Elevators should be leveraged for GEO and beyond, and (4) Space Elevators should be leveraged to deliver cargo, equipment, and supplies for Lunar and interplanetary missions. These factors lead to the realization that developmental planning must be initiated in the very near future for both advanced rockets and Space Elevators. As one who was involved in the interplanetary study by ASU and ISEC, I recognize the strengths and weaknesses of both architectures.

Rockets to Open up the Moon and Mars
with Space Elevators to supply and grow the colonies.

4.5 Summary: What does the new movement off-planet do to/for us as Space Elevator enthusiasts? It reinforces our critical nature as participants in the future. If we want to have colonies on the Moon, Mars, and beyond, massive movement of equipment and resources needs to lead the way. We are the answer! We must have a vision, inside the Space Elevator community, that is supportive of this monumental achievement and bring us into the planning for this embryonic endeavor. In addition, we must dream big and see the Space Elevator of the future. As we discussed in our last study report, ISEC feels:

> "The Space Elevator story is still being written. The Apex Anchor is where the Space Elevator meets the Shoreline of Outer-Space and where the Transportation Story of the 21st Century meets the Final Frontier."

Chapter Five: Architectural Engineering-Developing the Roadmap

5.0 Introduction: Our approach has been to help refine a necessary body of knowledge sufficient for the initiation of a Space Elevator development program. We believe that as we move into the third decade of this century, the implementation of a Space Elevator architecture is now necessary to support humanity's needs and dreams. I will make the bold statement now -

> "We are ready to initiate such a mega-project as the technologies are lined up as required." It is not only desirable for moving tonnage to orbit, but it is necessary for the health of our planet and humankind.

The process of Architectural Engineering is relatively new in the space arena as its focus is on major system development. The discipline has many components and when accomplished, leads to successful projects. This chapter will look at Architectural Engineering as a discipline and then show some of its strengths such as building a body of knowledge in parallel with developing roadmaps to proceed forward with a team.

5.1 Architectural Engineering:

Then an explanation of the Architectural Engineering process and where Space Elevators are in the sequence, or flow of development. This would explain how the design of Space Elevators have moved past the preliminary technological readiness assessment and ready to initiate segment level testing towards engineering validations. As we are ready to initiate a mega-project with a 10 to 12 year timeline, we envision working with the space community who are moving towards the stars and then enable their biggest dreams in the out-years.? Yes, we at ISEC feel that the Space Elevator is not elective, but is a MUST if our species really wants to develop colonies off planet and improve the health of the Earth. Our particular strength is massive movement of tonnage to high orbit. Seventy percent of the tether climber mass on the ocean surface will be delivered to GEO and/or inserted into fast transit towards the Moon or Mars.

5.1.1 Architectural Engineering Approach: The Architecture Engineering approach for developing a Strategic Plan for the Space Elevator Transportation System is as follows.

- Present substantiation of the seven elements of the Preliminary Technology Readiness Assessment (PTRA) statements. (accomplished at 2018 ISEC Conference)
- Evaluate the "for and against" aspects of all seven preliminary PTRA statements. (accomplished in IAA 2019 Study Report)
- Formally publish the Preliminary Technology Readiness Assessment (TRA) in the proceedings of the Conference. (accomplished in IAA 2019 Study

Report)

- Build roadmaps of Verification and Validation tests, experiments, and demonstrations as evidence that the engineering development of the Space Elevator is ready to proceed. Much of that roadmap will be the various verification and validation tests and demonstrations discussed in the ISEC position paper #2014-, "Space Elevator Architecture and Roadmaps."
- It is expected that the culminating Verification & Validation efforts will: a. a. Correlate to the segment structure of the Space Elevator Transportation System, b. Correlate to the seven cited items in the preliminary TRA, and c. Match the technology & engineering maturation index of the "Sequences"
- Seek funding to execute the roadmaps.

5.1.2 Example of Architectural Engineering - Developing Sequences: The answer of "How do you build a mega-project" centers around sequential growth. The answer of how you build a complex, massive project is straight-forward and has been practiced for centuries. The Panama Canal, the cross-continent railroads, and the remarkable aircraft industry have all be incrementally grown as the engineers and architects learned more and more about the project. In the case of the single space elevator growing into multiple Galactic Harbours around the world, the concept of sequences becomes real. The ISEC Chief Architect has laid out a series of events that lead to our preferred destinations. "This process is the source of our technical and intellectual fuel. Many of the early steps will be repeated until we "get it" and until we "get it right"; the essential definition of perseverance. By "get it", I mean engineering validation. By "getting it right", I mean a Space Elevator transportation system design. Let's talk about the first few steps in the Sequences."[8]

"You build something that has never been built before by persevering; relentlessly. We must prevail. We must not fail our vision. But we need a playbook! This Architecture Note is about that perseverance playbook. We call that playbook "Sequences." The sequences for a Space Elevator Mega-Project development are:

Space Elevator "Sequences" – Here are the 8 steps.

1. Pathfinder
2. Seed Tether
3. Single String Testing
4. Operational Testing,
5. Limited Operational Capability (LOC),
6. Initial Operational Capability (IOC),
7. Capability On Ramps leading to FOC
8. Full Operational Capability (FOC)

[8] Fitzgerald, Michael, "Architecture Note #6, "Taking the Space Elevator from now, to then, and beyond. We need Sequences." Technical note on ISEC website (www.isec.org).

There are several Architect's Notes that expand on these concepts and approaches. (see Architect's Notes 6, 7, 8 on www.isec.org)

5.1.3 Example of Architectural Engineering - Adjuncts: In addition to defining the baseline of the architecture, the team must define, care for and upgrade or eliminate alternatives to the baseline design. For the Space Elevator at this time, there are three adjunct elements to the basic architecture. They are:

1. Space Debris Adjunct (Mitigation) -- The Space Elevator will establish a close operational relationship with the space debris mitigation systems that will be operating in near Earth within the next decade. The space debris “chair” will be a permanent member of the HQ/POC, and be charged with supporting or providing awareness, warning, active defense, passive defense, and (if needed) recovery after a debris event.
2. Space and Surface Object Adjunct (Situational Awareness) -- There will be continuous monitoring and assessment of everything in the various domains of the Space Elevator. This would be seen as situation awareness, but is far more complex to include all the business aspects of care and feeding of customer products.
3. Client Support and Management Adjunct -- This additional tasking for the operations team is essential to keeping the customers satisfied and involved.

5.2 Developing a Body of Knowledge

Recently, a visitor to our International Space Elevator Consortium (ISEC) conference was quoted as saying, "You have a remarkable body of knowledge at www.isec.org. He was referring to the efforts of many scientists, engineers, and project/program professionals over the last 8 to 10 years. The leap in quality and currency shows that the Space Elevator is indeed twenty years beyond Dr. Edwards' breakthrough accomplishment saying "it can be done." What is amazing are the conclusions from this body of knowledge: (ISEC Studies at www.isec.org)

1. Space Elevators are ready to initiate a developmental program
2. The tether material has been produced in the laboratory for the needed strength (150 GPa) and continuous length (1 meter per minute production) (note; not both capabilities at once - yet). This 2D material will be ready for the development team.
3. Space Elevators enable Missions off-planet with robust cargo movement as a complementary access to space with rockets.
4. Space Elevators are environmentally friendly in operations and enable Space Based Solar Power to eliminate hundreds of coal burning plants.

Body of Knowledge - Current: The principal source for the following information is at www.isec.org. The following breakout explains how the body of knowledge is stored on our website.

5.2.1 ISEC Studies: Latest engineering, management, operations, and developmental issues addressed in year-long studies conducted by Space Elevator experts. Download all

12 of these ISEC study reports in pdf for free at www.isec.org. I am particularly proud of our latest year-long study entitled "Space Elevators are the Transportation Story of the 21st Century." This study report places Space Elevators into the near future and shows how they support critical missions. One such mission is the enabling of Space Based Solar Power. This mission will lead to a much cleaner global environment by eliminating hundreds (or thousands) of coal burning plants. The report also shows how to support Mars colonies and Lunar villages by supplying their needs. In addition, this report illustrates research accomplished by ISEC with Arizona State University showing the strengths of Space Elevators for interplanetary missions. Can you imagine 61 days to Mars? How about daily departures to Mars (no 26 month wait)? In addition, Space Elevators enable a tremendous benefit with massive cargo movement (170,000 tonnes per year to GEO and beyond). All this is accomplished with the Space Elevator architecture as a complement to rockets. This Dual Space Access Architecture (rockets and Space Elevators) is complementary and compatible - not competitive.

Table 5.1, ISEC Studies

Year	*Title of ISEC Yearly Study Reports (www.isec.org/studies)*
2021	Design Considerations for the Space Elevator Climber-Tether Interface - just starting
2021	Beneficial Environmental Impacts of the Space Elevator - in work
2020	Space Elevators are the Transportation Story of the 21st Century
2020	Today's Space Elevator Assured Survivability Approach for Space Debris
2019	Today's Space Elevator, Status as of Fall 2019
2018	Design Considerations for a Multi-Stage Space Elevator
2017	Design Considerations for a Software Space Elevator Simulator
2016	Design Considerations for Space Elevator Apex Anchor and GEO Node
2015	Design Considerations for a Space Elevator Earth Port
2014	Space Elevator Architectures and Roadmaps
2013	Design Considerations for a Space Elevator Tether Climber
2012	Space Elevator Concept of Operations
2010	Space Elevator Survivability, Space Debris Mitigation

In addition, there were three other major studies conducted on the modern Space Elevator; by the International Academy of Astronautics and the Obayashi Corporation.

Table 5.2, Other Studies

Year	*Title of Other Study Reports*
2019	The Road to the Space Elevator Era - IAA (2015-19)
2014	Space Elevators: An Assessment of the Technological Feasibility and the Way Forward - IAA (2010-14)
2014	The Space Elevator Construction Concept - Obayashi Corporation
	IAA - International Academy of Astronautics (https://iaaspace.org) https://www.obayashi.co.jp/en/news/detail/the_space_elevator_construction_concept.html)

5.2.2 References and Citations: These are listed by major topic (over 750 titles available). The breakdown covers the following topics: Baseline Documents, Architecture, Management, Tether Design, Tether Dynamics, Earth Port, Headquarters/Primary Operations Center, GEO Node, Asteroid, Lunar and Mars Elevators, ISEC Reports, Systems Engineering, Tether Materials, Space Elevator Environment, Tether Electrodynamics, Multi-stage Space Elevator, Tether Climber Design and Power, Apex Anchor, History, and Miscellaneous.

5.2.3 Webinars: Recently, the modern Space Elevator has been discussed within webinars that are accessible on ISEC website as well as YouTube:

Table 5.3, Web Offerings

Topic	***Date***	***Presenter***
Space Elevator Visions and Challenges	11/20	P. Swan
Today's Space Elevator	4/20	P. Swan
Graphene: the last Piece of the SE Puzzle	4/20	A. Nixon
Methodologies for Mitigating Risk to Lower Reaches of SE	8/19	S. Roberts
How the SE Work: Physics Concepts	7/20	D. Wright
Architecture Engineering for the Space Elevator	8/20	Fitzgerald
Applications and Uses of Robotics for a Space Elevator	7/20	C. Orrock
Space Elevators, podcast with Russell	12/20	P. Swan
Dual Space Access Architecture	10/20	P. Swan
Beneficial Environmental Impacts of Space Elevators	10/20	P. Swan
Space Elevator 101, Status and Architectures	5/17	P. Swan
Visionary Space Elevator Architectures	5/17	P. Swan
Are you Ready to Hop on the Elevator to Space?	5/17	P. Swan
Space Forward	1/21	Bernard-Cooper

5.2.4 Current studies: The two on-going studies are:

- 2021 - Design Considerations for the Space Elevator Climber-Tether Interface - The purpose of this study is to assess the climb-ability of the tether climber designs with the newly designated tether material: single crystal graphene. The results, at the half way point look very encouraging.
- 2021 - Beneficial Environmental Impacts of the Space Elevator - This study has been renamed the "Green Road to Space," as it has shown that using electircity to raise payloads to GEO and beyond without burning rocket fuel in the atmosphere is carbon neutral (or even carbon negative). In addition, with the ability to lift massive payloads to GEO, the Space Elevator is enabling to Earth Friendly missions not previously beleived doable with the current rocket architecture.

5.2.5 Architecture Notes: On our website there is a list of insights that are presented by the Chief Architect. This has crossed all the disciplines and approaches to a mega-project while focusing on the Space Elevator development. At the present time there are 35 notes ranging from definition of the sequence of events to achieve final operations to insight into interface control documentation.

Note	***Title***
1	Modular Construct
2	Business capture
3	Businesses offerings
4	Space Elevator Baseline
5	The Galactic Harbour
6	SEQUENCES
7	SEQUENCES
8	SEQUENCES
9	Strategic Approach
10	Discussion with Industry
11	Planning Horizons and Planning
12	Successful Conference
13	Communications
14	Delineation
15	Galactic Harbour's Full Operations
16	The SE is closer than you think
17	Strategic Approach to a Plan
18	OUTREACH
19	Is the Space Elevator a Rope
20	Baseline Change Management
21	FINAL ad Astra article
22	ROBOTS
23	Do You Know the Way Final
24	Path to Tech Ready
25	Space Debris Mitigation
26	Road signs and Burma Shave
27	FREE Delivery is an Essential
28	Coming Attractions
29	Call for Improvements
30	The Space Mosaic
31	Space Elevator Self Awareness
32	Testing a MEGA PROJECT
33	Architecture Engineering at the interface
34	Space Elevator Enterprise System
35	Apex Enterpise Region

Table 5.4, Architecture Notes

5.2.6 Frequently Asked Questions: Over time, certain questions are asked with both a lack of understanding and a curiosity. ISEC has a set series of answers for the basic questions, as shown in the following short descriptions.

<u>How strong does the material have to be?</u>
The first important term for this question is Specific Strength. A spider web might not seem very strong but it has a high Specific Strength because of what it can hold versus its thickness. This is very important for a Space Elevator because all of the material will have to be lifted into space and because the Tether will have to be able to hold itself together over a great distance. The standard unit of measurement for Specific Strength is stress/density with the unit Pascal/(kg/m3), for our purposes this can be adjusted to be 1GPa x cc/g = 1 million Pascal/(kg/m3)). For simplicity ISEC has adopted the measurement scale of Yuri's, named after Yuri Artsutanov, where 1 MYuri is equal to 1 GPa x cc/g. Steel wire has a specific strength of about .5MYuri. Now we enter the realm of what is technically needed to build a Tether into space versus what is required to make a practical Space Elevator. A Tether with a specific strength of 25MYuri could be built with ? but it would require a lot of mass and would not really be able to lift much. In the Space Elevator Feasibility

Condition, the Spaceward Foundation's Ben Shelef discusses this problem in detail and shows how several factors enter into the question. The bottom line is that stronger is better with 30-40 MYuri's being the best bet for a practical Space Elevator in the near term, well within the predicted limits for carbon nanotubes and single crystal graphene. Less initial material and more payloads to orbit will increase the rate at which a Space Elevator becomes a profitable venture. The recent discovery and production of a 0.5 x 0.1 meter single crystal of carbon atoms one layer thick has opened up the real possibility that a tether can be developed in the next few years. The material for the space elevator appears to be here - in the laboratory.

How will the Space Elevator Work? The Space Elevator stays vertical because of its mass rotating at high velocity at great distance above the Earth. Imagine you are holding a rope with a weight attached to the end. If you swing the rope in a circle at a sufficient speed, the rope will become taut, revolving about your hand. The force pulling the rope taut is known as centrifugal force. This same centrifugal force, generated by the rotation of the Earth, will pull the Space Elevator Tether upwards into space (outwards from the Earth). The outward force stabilizes the Tether with enough energy to allow 20 Metric Ton Tether Climbers to pull down on it and climb vertically. Routinely and daily a Tether Climber carrying cargo will be attached to the Tether at the Earth Port. The Tether Climbers will ascend the Tether, quickly leave the atmosphere and begin to make their way past Low Earth Orbit altitude, between 160 and 2000 km up. After about seven days, the Tether Climber will reach Geosynchronous Orbit where cargo can be off-loaded. The cargo that remains on the tether above Geosynchronous Orbit will be moving faster than required to stay in orbit and can be released and sent to destinations such as the Moon or Mars. The Tether Climbers will then ascend to the end of the Tether where they will become part of the Apex Anchor as counter-weight not always!?.

What is a Galactic Harbour? A space elevator is a tremendous transportation infrastructure leveraging the rotation of the Earth to raise payloads from the Earth's surface towards space and our solar system. It is indeed a part of the global transportation infrastructure.

In a mature environment where space elevators are thriving in business and commerce, there would be several (probably up to six) spread around the equator, each with a capability of lifting off greater than 20 metric tons of payload per day, routinely and inexpensively. The Galactic Harbour will be the area encompassing the Earth Port [covering the ocean where incoming and outgoing ships/helicopters and airplanes operate] and stretches up in a cylindrical shape to include tethers and other aspects outwards towards Apex Anchors. In summary, customer product/payloads [satellites, people, resources, etc.] will enter the Galactic Harbour around the Earth Port and exit someplace up the tether [to LEO, GEO regions, Mars, Moon, asteroids, intergalactic, and towards the sun, dependent upon where it is released. The "Galactic Harbour" is identified to be the transportation "port" for the total transition from the ocean to release in space. The port would be three dimensional, not surface only. The concept is the payload comes into the Galactic Harbour. It is then processed and released at some pier.

The GEO Node is a good example of where a communications payload would be prepared for release, powered up, checked-out, and then released to float(orbit) towards its assigned slot at GEO. The intra-transportation is very similar to a train operation, movement on rails from one station (Port Pier) to another. The difference is the Galactic Harbour will be up to 100,000 km high for payloads to be released at Apex Anchors.

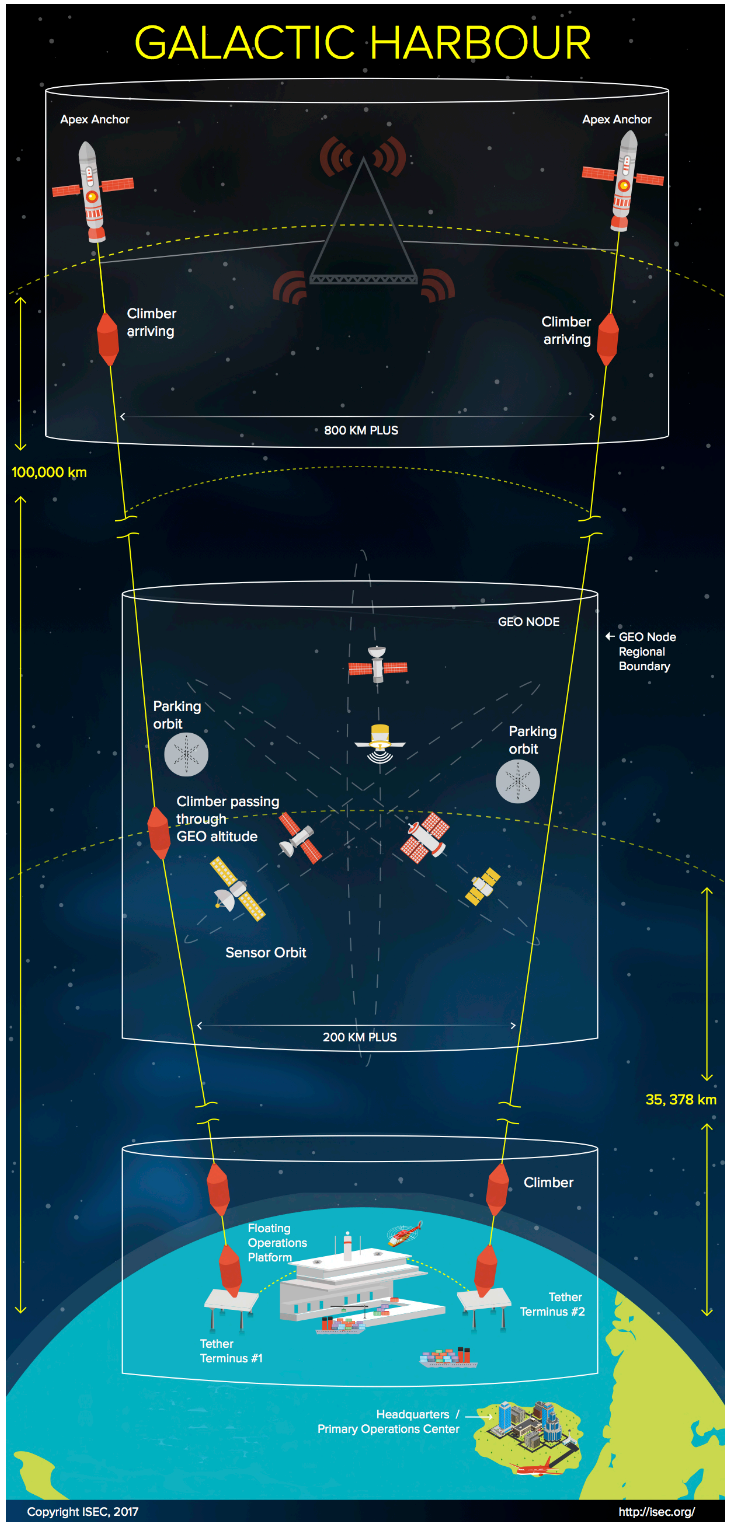


Figure 5.3, Galactic Harbour

The Galactic Harbour is the unification of Transportation and Enterprise. As payloads start to move throughout the space elevators, a core construction priority will drive businesses that will then lead to expansion beyond traditional functions. One projection is that the GEO Region will entice the construction of large enterprises to support non-traditional space businesses. What one sees now are a magnificent, large commerce and industrial regions in space, supported by this new, revolutionary space access transportation system; a space elevator. A needed capability is the generation of power to be projected down to the surface of the Earth from GEO. This Space Based Solar Power will no longer be restricted by huge costs for access to the orbit. Inexpensive delivery of payloads to GEO for construction purposes will lead to inexpensive power with almost zero carbon footprint on the surface of the Earth. Another mainline purpose will be to provide an inexpensive access to all planets in our solar system (as well as our own

Moon) with routine release and capture enabled by the lack of a need for huge rockets and consumption of massive amounts of fuel. As the space elevator is built and deployed, the:

Galactic Harbours will Unify Transportation and Enterprise Throughout the Regions.

5.3 Maintaining a Baseline status:

First, let us recall our definition of IOC for the Space Elevator Transportation System; our first destination at the end of development: The Space Elevator Transportation System is comprised of one Earth Port with two tether termini, Apex Anchor supporting 100,000 km Tether, 14 Tether Climbers, and a single Headquarters and Primary Operations Center. The GEO Node supports the Space Elevator Transportation System with a range of "overhead' functions; e. g. test, safety, and support. As described in section 4.2 previously, The current baseline is specifically seen as:

1. One Earth Port Floating Operations Platform, Two Tether Termini, Access City
2. One GEO Region provides support to a range of space based enterprises: Space Based Solar Power collection, Space Based factories, satellite repair and satellite refuel.
3. One Apex Anchor, interplanetary departure support,
4. One HQ/POC, a major portion ? at the Earth Port FOP, a substantial portion of the HQ/POC
5. Two Tethers
6. 14 operating tether climbers.

Figure 5.4, Earth Port

In addition, there are three adjunct elements to the basic architecture. They are:

1. Space Debris Adjunct (Mitigation) -- The Space Elevator will establish a close operational relationship with the space debris mitigation systems that will operating near Earth within the next decade. The space debris "chair" will be a permanent member of the HQ/POC, and be charged with supporting or providing awareness, warning, active defense, passive defense, and (if needed) recovery after a debris event.
2. Space and Surface Object Adjunct (Situational Awareness)
3. Client Support and Management Adjunct

When the kick-off of the Program Start occurs, this baseline will become part of the well known process of "maintenance of the baseline." A process will be put in place to also improve the baseline through a "Control Board." Mega-projects live and grow based upon maintenance of the "where we are going with what capabilities" document. One major component of this process is the initiation of the "Call for Improvements" events across the schedule. When it is determined that there might be a better approach, the call goes out and people respond with ideas that can be incorporated through a well know process. This limits the confusion while allowing for good ideas to surface and become part of the baseline.

5.4 Building Roadmaps within the Mega-project:[9] This chapter is a discussion of how we can get to an implementation plan for each of the Five Segments[10] of the IOC Space Elevator:

- Marine Node Segment
- Climber Segment
- Tether Segment
- Apex Anchor Segment
- Headquarters and Primary Operations Center (HQ/POC) Segment

We are going to get there by having implementation plans for each of the five segments of the Space Elevator Enterprise. There may be more than five segments, as we develop the total infrastructure; but, we'll deal with those later. The point is that we currently see five segments and are trying to visualize these five pieces of the enterprise.

5.4.1 Circumstance to Strategy to Plan: As the road mapping team stood at the starting line, we had gathered the several ISEC and AIAA publications, the proceedings from a few of the ISEC annual conferences, and even some international publications. This library had examined and discussed Space Elevators from any number of views. One discussed the Concept of Operations, another discussed the Elevator's high level architecture; and yet another registered an assessment of the technological viability of the whole thing. The team even looked at what was going on around the world. These documents provided valuable, diverse points of view which we sought to distill into a strategy, to converge on an understanding of what we needed to get to the Initial Operational Capability. During our road mapping effort, it seemed evident that within the envisioned Space Elevator Architecture, and its living Space Elevator Enterprise, a number of new entities and technologies are required. Further, new engineering approaches need to be instantiated and new materials need to be applied as the foundation of the Architecture. In street talk, we need new stuff, new ways to make it, and new ways to operate such things. Where are the Wright brothers and Kelly Johnson when we need

[9] This section comes from the ISEC Study Report Space Elevator Architecture and Roadmaps, Fitzgerald, Penny, Swan and Swan, 2014.

[10] These Segments are the result of an initial Requirements Analysis and Requirements Allocation activity of the standard System Engineering approach. Interface Management, another standard function, is addressed in Chapter 9.

them? We are not intimidated by all this, just cognizant of the challenge. Perhaps this is the challenge of our time.

5.4.2 Circumstance and Strategy: Nominally, a Technology Development Plan is needed. To get to that plan, the International Space Elevator Consortium will base its path to the initial operating capability (IOC) architecture based upon a technology development strategy of "Show Me." In our view, the "Show Me Strategy" begins with a set of well-constructed simulations and experiments. We feel that a successfully executed strategy will convince funding sources (e. g. foundations) that our vision is worthy. A funded strategy is a plan.

5.4.3 Strategy to Plan: Given attainment of sufficient maturity, the efforts are then blended into the program's risk management approach, including approaches to "buy down" the risk at a pace consistent with program execution, schedule and cost. The distinction made here between technological maturity risk and the program's risk management approach is a subtle but important one. The assessment of an item's technology maturity gains its access to the program. If it's not mature, then the technology is not part of the program or goes on to a later "on ramp." Once part of the program, the item goes through the program's risk management program where it's engineering, design and mission value progress are closely monitored.

5.4.4 Transformation to a plan: According to our strategy, the Space Enterprise team will get to the implementation phase by following the pathways identified in the road mapping process. Until this point, the road mapping process has focused on engineering, technology testing, analysis and such. In order to transform to an executable effort, schedule and funding must be fused with technical objectives. The Five Pathways must attain a planned sequence structure without losing the technical relationships established in the road mapping process. Our approach to that transformation is straightforward. We retained the structure of the Work Breakdown that we contrived early in the road mapping process, inserted the identified tests, experiments, analyses, etc., and then rotated the entire structure, overlaying it onto a schedule. It isn't a trick. It is a reformation planning effort that generates the technical information needed to proceed to design and development.

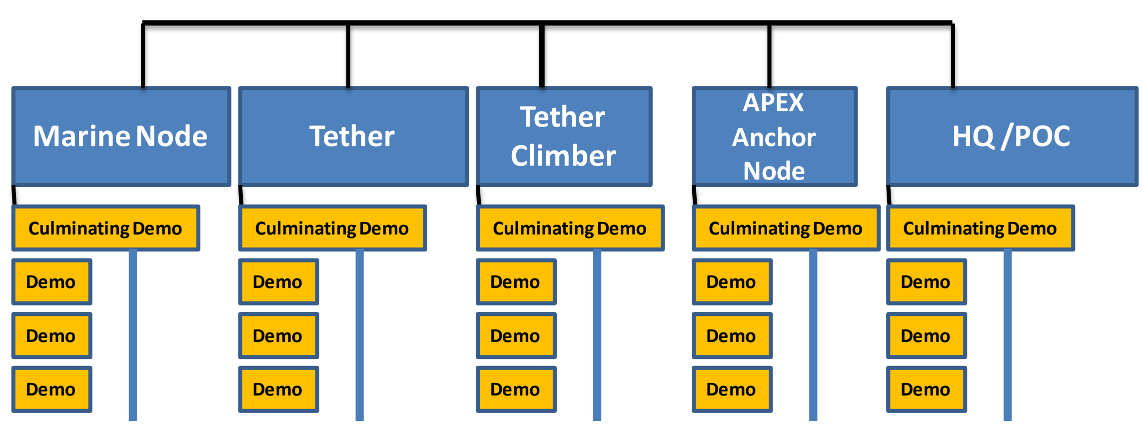


Figure 2-1 Initial Transformation

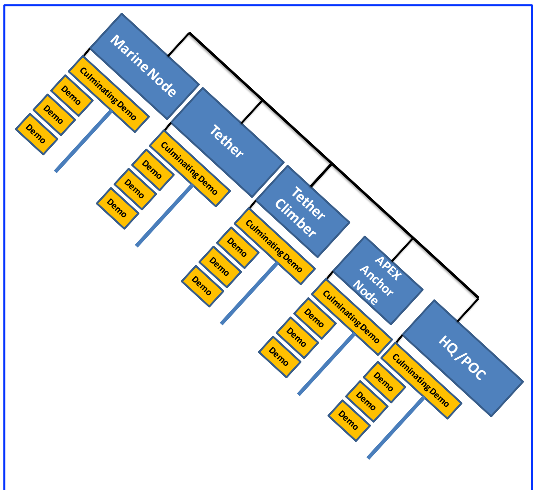


Figure 2-2 Continuing Transformation

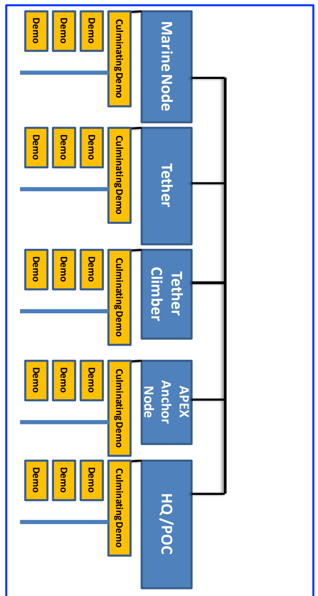


Figure 2-3 Continuing Transformation

Figures 5.4 & 5.5 & 5.6, Rotating the Transformation into a Plan

5.5 Getting to the IOC Architecture:

The graphics below depict the parallel Roadmaps that result in the transformation into pathways.

The Work Breakdown of the entire technical Architecture of the Space (IOC) Enterprise is reviewed. The duration of various tests and demonstrations are considered in the transformation. This is not drama, it is simply determining how long each of the tests and demonstrations might take if sufficient resources are available.

Figure 5.7, Test Campaign

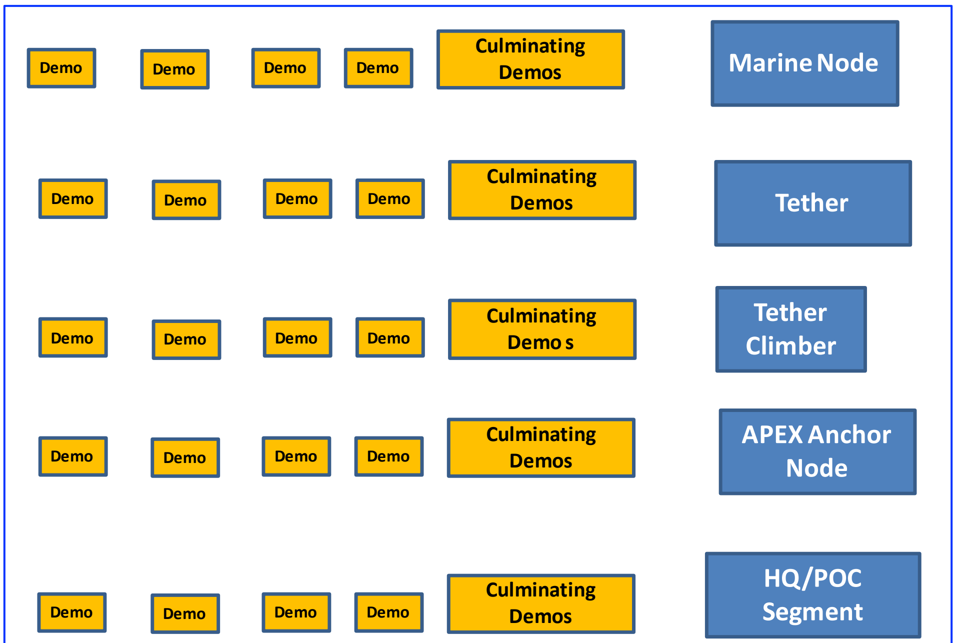


Figure 2-4 Five Pathways of an Executable Test Campaign.

At this point each of the paths must have the strength to move from an idea (the work breakdown structure) to the self-supporting test sequence needed to sensibly arrive at each culminating demonstration. The paths must cover the effort to lift immature technologies to an engineering approach for the culminating demonstration and be the basis for the design & development phase. The culminating demonstration should be viewed as a proto-flight, if appropriate. It needs to be much more than a feasibility demonstration, it must be convincing to the investor community, and must be supported by technical content acquired throughout each pathway's execution of multiple test events.

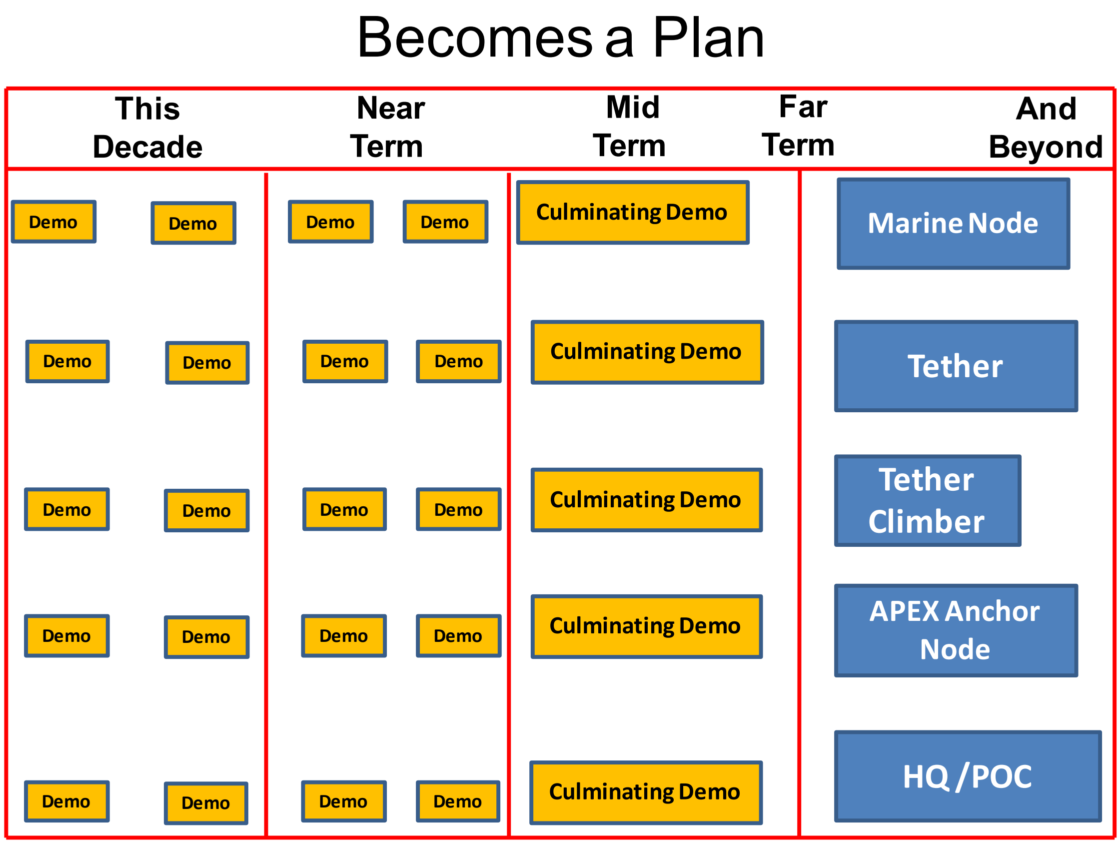


Figure 2-5 Becoming a Plan

Figure 5.8, A Plan is Formed

As we approach the culmination of the transformation, we will be prepared to execute the campaign of tests, analyses, inspections, simulations and experiments that lead to the culminating demonstration These achievements will posture our team as ready to build the necessary implementation plans: the Five Plans for each of the Five Segments. The initiation of the design and development phase of the Space Elevator Enterprise is here. Now, we are ready to start!

An Example of a Culminating Demonstration could be the Definition of a Pathfinder in Low Earth Orbit, shown on the next page. This is a very preliminary look at the demonstration, but should lead to one such activity along the path to operations.

Definition of Pathfinder

After space elevator culminating demonstrations across the five segments, the validation for the customer could be a single full up system of systems integration test that shows the interplay across the segments as well as within each segment. There is a concept surfacing within the space elevator community that sees a full-up test in space once the culminating demonstrations have been accomplished with individual segments. This would be designed to show the customer that the concept works in the environment of a space elevator, just at a smaller scale prior to full commitment. The concept is to have a long [estimate 1,000 kms] tether [of same material but not necessarily with the same tensile strength required for the space elevator] being placed at 2,500 km altitude circular orbit. The initial spacecraft would resemble the future deployment satellite with both a smart satellite representing the Earth Port and a smart satellite representing the Apex Anchor, connected by a 1,000 km tether on a reel. The system of systems integration test would validate the following actions to ensure design maturity and concept viability.

- Establish a Center for Operations – a start-up Head Quarters & Primary Operations Center
- Placement in Orbit (into LEO then transfer to 2,500 km circular)
- Stabilization in circular orbit [2,500 km altitude]
- Deployment of tether under control, with reel in-out capability [Apex Anchor deploys as upper terminus with the Earth Port deployed downwards]
- Full tether deployment [1,000 km length] developing reel out techniques
- Demonstrate Tether similar in weave and layout with a taper ratio – however, not necessarily the same tether tensile strength for this demonstration [can be manufactured earlier]
- Demonstrate Tether material maintenance, repair and splicing.
- Apex Anchor Controls dynamics with thrusters and reel-in reel-out capabilities
- Test Earth Port control of dynamics with thrusters and reel-in reel-out capabilities
- Representative Tether Climbers are deployed and climb up and down with mechanisms representing the final design of the space elevator tether climbers – recognize tether control from climber motion
- All actions controlled and monitored from the HQ/POC.
- Release of tether climbers as last tests [of course release to deorbit for debris cleanup]
- Move system to terminal orbit [either reenter in 25 years or place above all LEO satellite orbits].

Figure 5.9, Pathfinder

5.5.1 The Implementation Plans: Each of the five segments' pathways will be constructed as an executable test campaign. The campaigns are composed of a taxonomic sequence of test and demonstration events that we have been talking about for months. Each event will have entrance and exit criteria and, as we approach the culminating demonstration, each event will have more specific exit standards.

The Architecture & Roadmap (A&R) team saw Architecture implementation planning in three levels of detail, or depths:

- Preliminary Implementation Plan
- Detailed Implementation Plan
- Technical and Mission Review

The implementation plans are substantive items; and, given that they are seen as years in the future, the team portrays that each Segment's Implementation Plan will be modified over the course of time. Build a little, test a little, and build more. In response to the achievements of the preceding test event within the campaigns, and in consideration of the development progress, each step must be compared to the risk state of each segment as the demonstrations progress.

The standards of specification for the three implementation planning documents were not delineated by the R & A team; but, it is clear that the Enterprise Segments must ultimately combine into the integrated Space Elevator Architecture. The Implementation Plans are foreseen as products of the road mapping process on the one hand and the forecast of technical character on the other. These plans will actually contain libraries of the fundamental System Engineering documents essential for a solid design process to be executed with specification documents, requirements documents, concept of operations, management plans and more. The pathways leading up to an implementation phase gave us the information and the insights to start. Not discussed in this document, but of equivalent importance, are the integration processes that enable the emergence of the single Space Elevator Architecture from the five Segments.

Chapter Six: Technologically Ready to Start

6.0 Where is the Space Elevator in Development?

The question on the table is: are the technologies for development of a space elevator infrastructure available now? My answer is yes - gained from studies at the International Academy of Astronautics, ISEC and ASU. The following is a multi-page summary of the specifics to this assessment; however, most people are only interested in the tether material as that has been holding us back for the last 20 years. Excellent news on that front as a new form of materials was discovered about 15 years ago and has shown that "2D" materials can be produced in a continuous process and strong enough for Space Elevator requirements - yes, it is far from ready - yes there are many issues - yes there are concerns. However, I believe (with the support of my expert on Single Crystal Graphene) the material will be ready for us when we need it. A mega project takes time to initiate, then develop the separate segments, then pull it together into a system of systems and then deploy it in space. I believe the material will be ready for the implementation when the other segments are lined up appropriately. Now, is the time to initiate serious research and developmental planning for the future "second lane" to space. Visions drive mega-projects and it is time to start the Space Elevator development. The following sections address key elements of assessment of technological readiness:

> Development Status: The development of Space Elevators should be initiated NOW for two reasons.
> First: The Demand Pull for customer delivery of massive tonnage to GEO and beyond cannot reasonably be accomplished when the delivery percentage to destination is less than 2% of the launch pad mass.
> Second: The situation has been altered for the Space Elevator development status. We now have a material that can be used for our tether.

6.1 Four Phase Developmental Approach:[11]

When one looks at the status of the development, as shown with the Engineering Development Stages approach, it has been shown that the status is someplace been the end of the first box and the beginning of the second box.

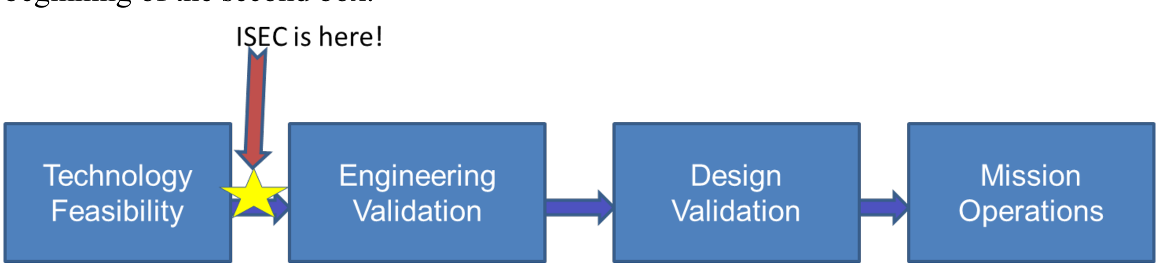


Figure 6.1, Four Phase Developmental Approach

[11] Fitzgerald, M. Swan, P. "The Technical Maturity and Development Readiness of the Galactic Harbour," IAC-19-D4.3.2, Washington DC.

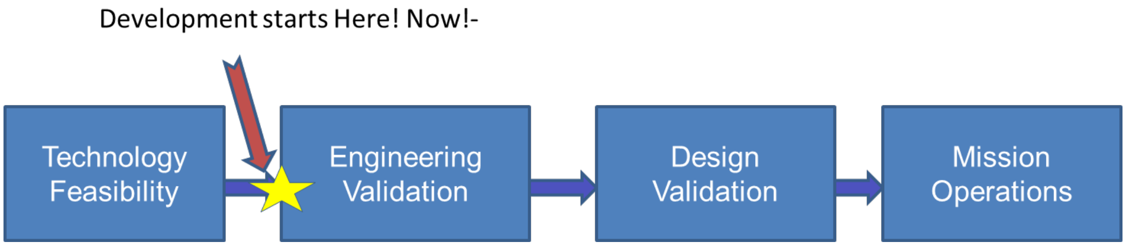


Figure 6.2, Entering Phase II

The ISEC Development Plan has a Technology Development Strategy based on a constant & recurring attitude of "show me" manifested in a taxonomy of tests, demonstrations, simulations, and experiments that reward success with admission to the next set of tests, demonstrations simulations and experiments; an iterative approach to program risk removal. The roadmap depicts a continued inspection of the technical veracity of ISEC progress toward meeting the mission objective. Frankly, this approach has been in place for some time; about 13 years. But in the last six years or so, ISEC saw the need to codify and compare the metrics of technology readiness with the variety of "show me' techniques available. The ISEC Technology Development Roadmap – based on "show me" ... is marked by four Phases, as shown. The roadmap has two intermediate destinations; the preliminary Technology Readiness Assessment (at the end of Phase One), and the start of Engineering Validation (Phase 2).

The ISEC Technology Development Roadmap becomes the ISEC Technology Development Plan with the identification of the specific approaches necessary to execute the Strategy. In this context, the plan will be executed in four phases; from now through Operations. Substantial funding and industry involvement is needed; starting with Engineering Validation.

6.1.1 Phase One: Assess Technology Feasibility: This phase is well underway. In fact, for the Space Elevator Transportation System; it is essentially complete. The ISEC team has been assessing the technology feasibility situation since 2006. In recent times, the team has established an open dialog with several current and former members of the space industry and learned a great deal about the technologies being matured into engineering approaches, and those that will be available later. During Phase 1, ISEC program team has:

- Determined readiness state: Determined if the technologies are State of Art (SOA) or State of the industry (SOI) or State of the Market (SOM). "SOA" means that only one industry member holds the critical technology; "SOI" means that a few competent industry members can play; and "SOM" means that the technology is widely available and widely used.
- Established readiness level rationale (e. g. TRLs) for all portions of the Program: Ggiven that the technology availability has been demonstrated (SOA v SOI v SOM ... etc.) the level of readiness could be established for program segment, component or subsystem. Generally, TRL level 5 or 6 at the segment level would be expected for entry into design development (the Plan's phase 3). The show me

based taxonomy of readiness is well understood as we approach the beginning of Phase 2 and readiness will be documented by Industry in the official Technology Readiness Assessment later in Phase 2.
- Set Criteria regarding Engineering Validation: Modern acquisition approaches call for a Preliminary Design Review (PDR) during the Engineering Validation phase. This review is really an examination to show that the projected engineering approaches are valid. In this consideration "engineering validation" means that we can build it. If the valid technology exists, it cannot be included in a design based purely based on technology maturity. If a component is SOI or SOA, or is a TRL level 4, some engineering validation information is needed . within the PDR process. "Show me" means a lot at this point. These Engineering Validation efforts could begin now and progress through all segments of the Space Elevator Transportation concept.

6.1.2 Phase Two: Validate Engineering Approaches: This Phase begins soon after preliminary TRA is reached. The ISEC team will assign a wide range of engineering validation objectives to various members of the industry base. These have been called by some "sanity samples". Much of this information is likely to be competition sensitive, but broad insights will be gathered to loosen funding sources. Industry involvement is mandatory! The Phase Two activities are driven by six major activities:
- Can it be built? This is the fundamental question facing the ISEC team before it approaches Space Elevator Transportation System design. The ISEC team intends to describe the engineering approaches it envisions and examine determine the engineering approaches being considered by industry. The ISEC team will then ask industry to show how their engineering approach is valid and incorporates the fruits of the ongoing technology maturation.
- Examine Industry's Program Roadmaps: ISEC members saw a sample of these IRAD roadmaps during interactions with industry. It was clear from the samples that the range and number of needed engineering validation tests and demonstrations is substantive.
- Assess schedule & technical risk: This assessment is very real. The multiple tests, demonstrations and simulations are the path to ISEC program success; and they are the basis of a long sequence of engineering and design judgments. Conducting the numerous tests, resulting in the proper test data and performance insights is in itself a risky set of ventures --- but proceeding with the program without that thorough testing would be beyond risky; even foolhardy.
- Delineate On Ramp Criteria: Based on the information emerging through risk assessment above, ISEC will collaborate with industry re deferring certain functionalities (e. g. "late incorporation") or redefining the basic schedule. Setting on ramp targets for late incorporation is not simply delay; but rather a considered approach of when that capability is ("really") needed and whether subsequent maturity and testing will be fruitful.
- Set criteria and standards re Design Validation By the end of Phase Two ISEC evolves from determining that industry can build it to determining the efficacy of specific design approaches. Those design criteria and design standards need thorough evaluation for the sake of technical, schedule and/or cost risk. These

criteria and standards are to be assessed in Phase Three; using design validation information.

- Baseline Technical Performance: By the end of Phase Two, the performance of the envisioned concept can be predicted and will be "baselined" into a system performance specification.

6.1.3 Phase Three and Four Technology Development Plan: Phases 3 and 4 are part of the ISEC Technology Development Plan; but, become the Industry Prime contractor's System Engineering Plan for the Space Elevator Transportation System development program. The outlined activities of each Phase are included here for the sake of completeness. The efforts taken by the ISEC team to get the needed technologies matured (Phase One) and then assessed to be "engineering valid" (Phase Two) must not be left behind as some bureaucratic process. The judgments and efforts of Phases One & Two move forward into the program's subsequent Phases; - amplified by a System Engineering Management Plan, a Test and Evaluation Master Plan, a Risk Management Plan; and other discrete engineering process efforts – ultimately delivering on the promise and vision of those predecessor efforts.

Phase Three: Validate Design Approaches –

- Service the Risk Buy down
- Measure Design versus Performance Baseline
- Technical Performance Measures
- Establish Basis for Mission Assurance assessments

Phase Four: Assess Mission Operations Success –

- Establish Performance Envelopes for the operational system
- Terminate Risk Management Program
- Conduct Risk Monitoring with Good Tools
- Examine "On-Ramp Items"
- Baseline Operational Performance Measures

Note: Space Elevators are HERE, entering Phase Two
- Validate Engineering Approaches

6.2 Starting Phase Two:

We are ready to start the engineering validation phase based upon the legacy of analyses and assessment. During the assessment of this process [Swan 2019, pg 28] it was stated:

"The ISEC team has been assessing the technology feasibility situation since 2008. In recent times, the team has begun an open dialog with those members of industry, academia, and others; who could be the deliverers of ISEC solutions. Industry (especially) will show how the needed technologies are being matured and when they could be dependably available. These readiness assessments are the Phase One exit criteria:

- Document technology readiness state. Determine if the technologies are State of Art (SOA) or State of the Industry (SOI) or State of the Market (SOM)
- Establish readiness level rationale for all portions of the Program. Given that the technology availability has been demonstrated the level of readiness can be established for each program segment
- Set Success Criteria regarding Engineering Validation – the second phase. Prudent acquisition planning calls for an early design review. "Show me" means a lot at this point."

Phase two (second blue box) can begin now as phase one has been completed. Industry involvement is an imperative. Phase two activities are driven by six major activities:

- Examine Industry's production foundation
- Determine if the segments can be built
- Assess schedule & technical risk:
- Delineate design criteria
- Set criteria and standards to enter the Design Validation Phase
- Baseline operations performance:

6.3 Major Tasks inside a Mega-Project

In addition to understanding the Process Approach and identification of where Space Elevators are entering 2021, it is critical to understand new team tasks to accomplish. The next chart shows the major tasks that must be taken early in the development of a mega-project. The five tasks will be discussed next:

Table 6.1, Tasks for Mega-Project

	Major Tasks	***Status***	***Reference***
1	Certify Preliminary Technical Readiness Assessment	Completed	[Swan, 20018]
2	Examine Segment Level TRLs	Assessed and presented	[Swan 2019]
3	Substantiate that the Material is Available	Shown to be "long enough" and "strong enough"	[Nixon 2020]
4	Show the Culminating Demonstration Plan	Discussion leading to 17 segment demonstrations needed	[Fitzgerald 2014]
5	Establish a Preliminary Architecture established	Galactic Harbour, Earth Port to Apex Anchor	[Fitzgerald 2014]

6.3.1 Task One - Completed preliminary technical readiness assessment. This was the purpose of the International Academy of Astronautics Study reported out in 2019 [Swan 2019]. The following is a summary of their conclusions:

- The Galactic Harbour Earth Port è ready for an engineering validation program
- Space Elevator Headquarters / Primary Operations Center è ready to start an engineering validation program
- Tether Climber è Engineering model assemblies needed -- then start an engineering validation program
- GEO Node è Engineering discussions and demonstrations with key members of industry are needed along with collaboration / outreach with certain government offices.
- Apex Anchor è Engineering discussions and various simulations are needed. Near term collaboration with engineering organizations and academia should begin follow-on outreach to key members of industry and government. Engineering validation follows.
- Tether material è Prime material candidate is identified; and, production demonstrations are needed.
- Collision avoidance è Architectural engineering definition is being finalized. Candidate concepts are identified. On orbit performance demonstrations are needed.

6.3.2 Task Two - Examine segment level technologies . The 40+ team of global space experts looked at the technological readiness of the Space Elevator and concluded the following: [Swan 2019, pg 78]

> "The study team has been hard at work looking for the critical technology that would be too difficult or risky to lead to success. The bottom line is still that the material paces the development of the space elevator infrastructure development. When one looks at all the various technologies and where they are in the TRL evaluations common to NASA projects, the team has the following conclusions:
>
> - The Earth Port is buildable with today's technologies!
> - The Headquarters and Operations Centers are buildable today!
> - The tether climber is so similar to a normal satellite of today that there is no real challenge except the interface with the material, and that surfaces around the lack of information of the material to be chosen.
> - The GEO Node and Region is understandable and not an issue during development!
> - The Apex Anchor will be a challenge as its role is key to the building of the space elevator, but not an engineering and technological issue.
> - However, the tether material is the pacing item for the development of the space elevator. Currently, there are three viable materials that could grow into the needed strong enough and long enough material for a space elevator. The community has an active plan maturing these materials to mature to the level that can be implemented into a space elevator tether 100,000km long and strong enough to support multiple tether climbers against the pull of gravity." [note: single crystal graphene has made great strides and seems to be maturing towards "long enough"

and "strong enough." see next task]

6.3.3 Task 3: Substantiate the schedule and technical readiness of the tether material: The current understanding is that a material is available that is "long enough" and "strong enough." [Nixon 2020a webinar] "What would a Space Elevator Tether look like?" At the time of writing there are three potential materials that are light enough and strong enough to make the tether for the space elevator. Carbon nanotubes, Graphene and hexagonal Boron Nitride. Of the three-candidate materials graphene is emerging as the most likely at present because the industrial manufacturing process has advanced rapidly. Graphene can now be made at industrial lengths and speeds. The quality is not good enough for a tether at the moment but given the pace of manufacturing progress this can now be considered a credible future material. So, to answer the question posed at the start, a space elevator tether would look like a glittering sliver mirror ascending into the sky piercing the clouds to reach for space." [Nixon 2020b]

Figure 6.2, Projection of Tether Design

6.3.4 Task 4: Culminating Demonstrations required

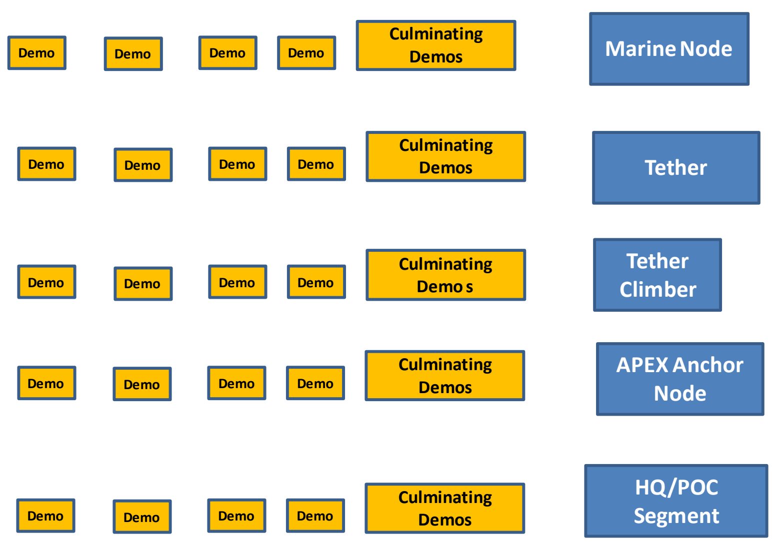


Figure 6.3, Plan in Place

The ISEC study in 2014 was entitled "Space Elevator Architecture & Roadmap" and laid out the culminating demonstrations for each of the major segments. This figure shows how they are arranged, from smaller tests to the final culminating demonstrations in each segment (this is an old chart and uses Marine Node instead of Earth Port as title). Each of these segments has a sequence of tests that will lead to the validation of the engineering and then production segments.

The following description shows the major Culminating Demo's for the Apex Anchor. In this article, only one list of demos is given as they are all recorded in the study. [Fitzgerald 2014 pg 9] The other Space Elevator Segments have similar demonstrations and are listed later.

The three culminating demonstrations for the Apex Anchor are as follows: [Fitzgerald 2014 pg. 47]

- Tether reel in and reel out.
- Thruster magnitude and direction.
- Support Customer Activities: When the customer starts to leverage the space elevator, the Apex Anchor will play a major part as a customer satisfaction arena. As the customer's satellite climbs towards the Apex Anchor, their needs will range from help in releasing the satellite from the tether, assembly of multiple parts to build a larger spacecraft, and acceptance of incoming payloads to the Space Elevator to be sent back to the GEO Node or the surface of the Earth. This ability to off-load and attach customer payloads at the Apex Anchor must be demonstrated, probably in space with appropriate accelerations.

Each of the major segments has a series of Culminating Demonstrations that must be accomplished in parallel so the mega-program can progress. They are discussed in the 2014 ISEC study. The program reality is that the architectural engineering team has shown the path to validation at the system level. A quick review of the ISEC Position Paper # 2014-1 – "Space Elevator Architecture and Roadmaps" reveals the scope of testing:

- The Earth Port - 4 Major Demonstrations
- Tether Segment - 13 Major Demonstrations
- Tether Climber - 8 Major Demonstrations
- Apex Region - 9 Major Demonstrations
- HQ / POC - 4 Major Demonstrations

6.3.5 Task 5: Show the Destinations. Preliminary architectures are laid out in many places with ISEC focusing upon the Galactic Harbour concept. The current expectation for the future is three Galactic Harbours with two Space Elevators each spread out around the equator. The Galactic Harbour was defined well in the ISEC Study "Today's Space Elevator." [Swan 2019]

6.4 Tether Material Status:

ISEC believes a material is in the laboratory and has been shown to approach the 150 GPa tether strength requirement. The new material [Single Crystal Graphene] could be manufactured in long lengths as "single crystals.12" (130 GPa, with a density of 2.2g/cc). The minimum requirement for Space Elevator tethers is approximately 84 GPa at this density. The estimate is for long tether material strong enough for Space Elevators is the late 2030's. A recent letter from Nixene Ltd. stated:

[12] Nixon, Adrian, Update on Graphene as a Tether Material. 2019 International Space Elevator Conference, Seattle, 16-18 Aug 2019.

"Joint planning between ISEC and Nixene Ltd anticipates the development testing and deployment of the Space Elevator tether within the next decade or two...."13

The following summation explains how single crystal graphene will enable space elevators, as the tether can be made from today's material.

- The tether can be produced in a continuous roll process
- It can be made to reach 100,000 km long through the atmosphere and space.
- It is strong enough to hold up itself and several climbers
- No other material can be long enough nor strong enough at this time.

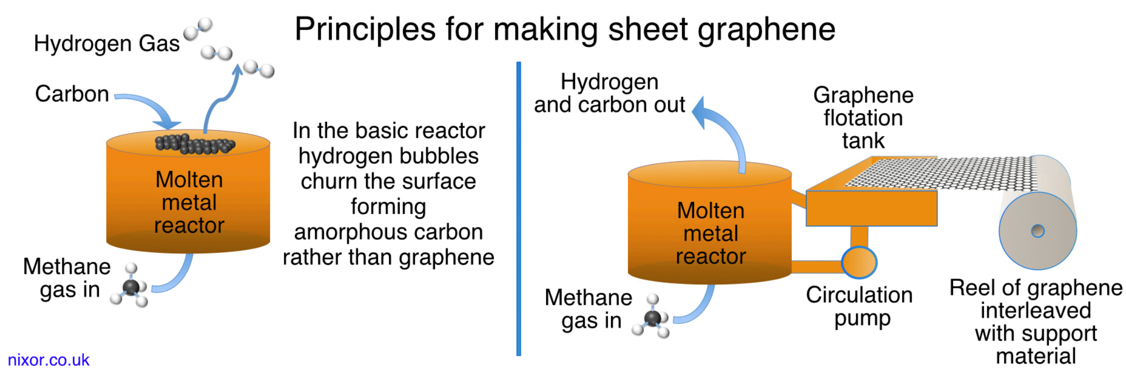


Figure 6.4, Overcoming CVD production problems: A continuous process (Slide from Adrian Nixon's presentation webinar June 2019)

Learning to extract best performance out of imperfect materials is a common engineering problem. Rare indeed is the design where all constraints and criteria are fully satisfied by a single solution. Two challenges that separate us from a current tether design become clear. The first, a challenge of assembly—how do we ensure uniform load distribution in our material, so that we can bring the nano-scale properties up to our macro-scale application. The second, a challenge of production—how to scale existing processes up to produce the volume needed. Neither of these challenges requires fundamentally new science or engineering. They require continued application of existing knowledge and skills. Based upon these conclusions, a number of recommendations can be made - the primary one is to encourage and support specific strength material development with the purpose of making them long enough and strong enough for Space Elevator tethers.14
As of the turn of the year to 2021, much progress has been accomplished. At the time of writing, USA based General Graphene stands out as the leading company of the moment for the following reasons:

- They have developed a very large-scale process capable of making sheet graphene on a scale of hundreds of square meters per year.

13 Adrian Nixon letter, to be expanded upon later

14 Swan, P., David Raitt, John Knapman, Akira Tsuchida, Michael Fitzgerald, Yoji Ishikawa, Road to the Space Elevator Era, Virginia Edition Publishing Company, Science Deck (2019) ISBN-19: 978-0-9913370-3-3

- Based on the work at Oak Ridge National Laboratory, they have the capability of growing large domains of single crystal graphene, at present around 300mm2. The team tell us there is no limit to the size of single crystal they will be able to grow with further development.
- The team has developed a transfer method that can place the graphene on plastic film or thermal transfer tape for further processing by customers.

In 2021, polycrystalline sheet graphene can be made in industrial quantities. Large-scale sheet single crystal graphene is capable of being made in the quantities needed. Given sufficient funding, the manufacturing of tether quality, large-scale sheet, single crystal graphene could be a reality within a decade.

6.5 Additional Challenges - There are several challenges that will require some outside of the box thinking and long range planning. Most of the authors of this report have been inside mega-project developments and recognize that early identification of puzzles enables success in the long run. Some of the challenges are:

6.5.1 Operating Safely inside the atmosphere (much of this section comes from papers by John Knapman[15] and Peter Swan[16])

Introduction: The space elevator needs to pass through the Earth's atmosphere so that payloads can be raised from the surface. However, the atmosphere is turbulent, with strong winds, ice and electric storms at many altitudes. A wise choice of location can reduce these effects, but not eliminate them. For example, the area of the Pacific to the west of the Galapagos Islands has experienced no hurricanes since records began in the 19th century. The anchor point at which the space elevator reaches the ocean is called the Earth Port. Above the atmosphere, the tether extends to the Apex Anchor, 100,000 km from Earth. It is designed as a thin ribbon one meter wide, curved to minimize damage from meteors and space debris. Within the atmosphere, a narrower ribbon of 20 cm has been proposed to reduce the effects of winds.

The tether climbers are to be powered by lightweight solar panels, and they will require protection in the atmosphere. Three solutions have been discussed:

1. Box Protection: One solution is to fold the solar panels and enclose them in a container. An alternative source of power is required while the solar panels are folded. Since this is only necessary for a few tens of kilometers, a lightweight power cable can be used without adding substantially to the weight of the total tether.
2. Spring Forward: A second method of powering the tether climbers while the solar panels are folded is to exploit the elastic properties of the tether. A modest variation in its tension will create sufficient force to lift a tether climber above the

[15] Knapman, J. and Swan, P., "Design Concepts for the First 40 km – A Key Step for the Space Elevator," *Acta Astronautica* (2013), DOI: 10.1016/j.actaastro. 2014.06.004

[16] Swan, P. C. Swan, Space Elevator Design Aspects for the Environment," IAC-12-D4.3.05, Naples Italy presentation, Oct 2012.

atmosphere, where it can unfold its solar panels and continue ascending under its own power. Once the tether climber has ascended for several hours and is safely out of the way, the Earth Port can pull the tether down in readiness for lifting another climber the next morning.

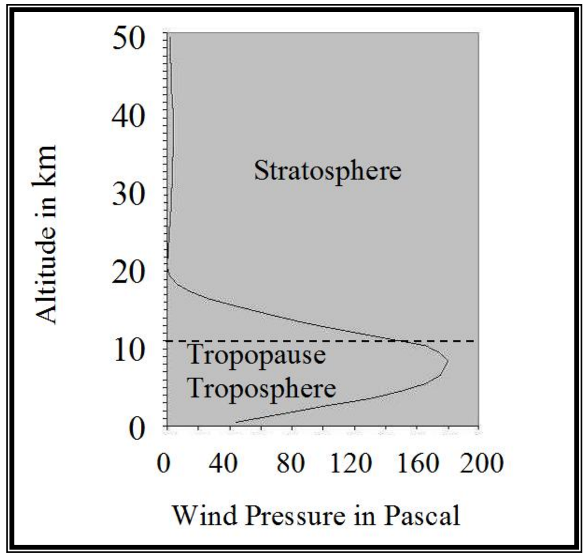


Figure 6.5, Wind Pressure[17]

3. High Stage One: A third method is to anchor the tether to a platform at high altitude. The platform is supported using an adaptation of the Lofstrom Loop. Inside evacuated tubes, a continuous stream of rotors travels from the surface up to the platform and down again. Deflecting the rotors creates a levitation force that holds up both the tubes and the platform. At the surface, the rotors travel round a horseshoe-shaped structure called an ambit so that they can travel up to the platform again and continue indefinitely. Magnetic levitation is used to minimize friction. High Stage One is designed to absorb wind and other atmospheric hazards without affecting the tether. Tether climbers can be kept above most of the atmosphere so as to protect their solar panels.

Atmospheric environment: Many effects occur within the first 60 kms of the tether, to include winds aloft, hurricanes, tornados, and lightening. This category of threats affects the tether and the climber in the lower reaches of the climb.

Winds Affecting the Tether: Winds are a challenge to the space elevator. In temperate latitudes, jet stream winds can exceed 100 meters/sec between altitudes of 9 and 15 km (Barry and Chorley, 1998). Global average wind speeds against altitude vary. The high speeds above the stratopause are of little consequence because of the extremely low density. Figure 6.x takes the atmospheric density ρ into account to reach an estimate of global average wind pressure ρv^2, where v is wind speed. Maxima may be four times as great as averages; that worse case effect can be demonstrated by multiplying the pressure scale by 16.

[17] nssdc.gsfc.nasa.gov/space/model/atmos/cospar1.html

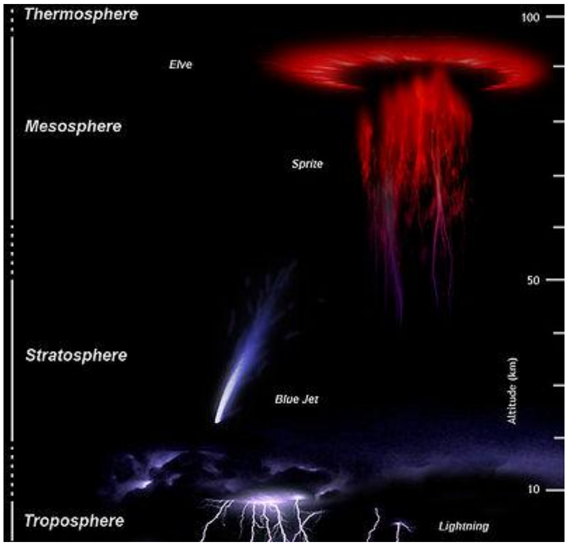


Fig 6.6, High altitude lightning and discharge phenomena[18]

Near the equator, there are only seasonal jet streams over Africa near latitudes of 15° N or S, and they do not occur over the equatorial oceans. Considerable design effort has gone into dealing with strong winds in the High Stage One option based upon the use of guy wires supported by the rotor via magnetic levitation. This is a great advantage over the alternative of trying to deal with these forces directly from the tether.

Atmospheric Lightening: Many people have studied the frequency of lightening strikes around the world and have discovered that there are multiple locations that do not have significant strikes or cloud-to-cloud electric releases. As a result, space elevator designers are recommending a quiescence location in the pacific west of the Galapagos along the equator. In addition, for the lower reaches of the atmosphere, lightening arrestors have worked for centuries. In modern times, additional approaches for releasing the energy prior to strikes have been developed such as laser ionization of the air to provide a path for the energy to reach the ground. As such, the Earth Port will have several choices in Stage One such as lightening arrestors and ionization lasers as standard equipment to keep the tether safe from atmospheric effects. If the Earth Port includes a High Stage One, the lightening phenomena become the concern of the structure going to 30-50 km, not the tether.

High Altitude: Choosing a site with few electrical storms means that high-altitude electrical phenomena are also likely to be infrequent. Locating the transfer platform at 30-50 km altitude will still expose the main space-elevator tether to elves, sprites and gigantic jets. These electrical phenomena occur at high altitude, as illustrated in Figure 6. Blue jets occur in the stratosphere, up to about 50 km; sprites and elves are twice as high. Another phenomenon, the gigantic jet, was only discovered in 2001; it reaches from the lower stratosphere up to 70 km. All of these are associated with electrical storms in the troposphere. Electrical breakdown above thunderstorms was first predicted in the 1920s; but, the first documented visual evidence was obtained in 1989.

As a result of these effects from electromagnetic discharges at altitude, the space elevator tether must be structured to handle massive current and voltage on limited occasions. This could be designed into the tether with a parallel lightening rod, multiple tethers separated by 100 km or so, or a way to isolate the tether from the grounding phenomenon

[18] en.wikipedia.org/wiki/Upper-atmospheric_lightning

in a way that ensures that the energy does not deposit itself on the tether. This topic is still to be studied in detail and must be understood to a more detailed level to ensure a design that is safe and secure.
Solution 1 - Box Protection: A container would protect a climber's fragile solar panels from wind, ice and electric storms. It could be lifted by the tether climber's own mechanism, or it could have a separate climbing mechanism. An advantage of a separate mechanism would be to give greater flexibility in the tether design. To reduce the effects of winds, the tether in the atmosphere is narrower than the one meter width it has in space. It could be even narrower than 20 cm so long as it has the necessary cross section of 10 mm2. However, the main tether would have to support the extra weight of the box with its climbing mechanism. Power for the box protection could be supplied from a cable connected to the surface. Graphene can be made to act as conductors, semi-conductors and insulators. Hence they can form a very light power cable for the box protection up to the required altitude of at least 40 km. At this point, the box releases the tether climber to continue under its own solar power, while the box returns to the surface.

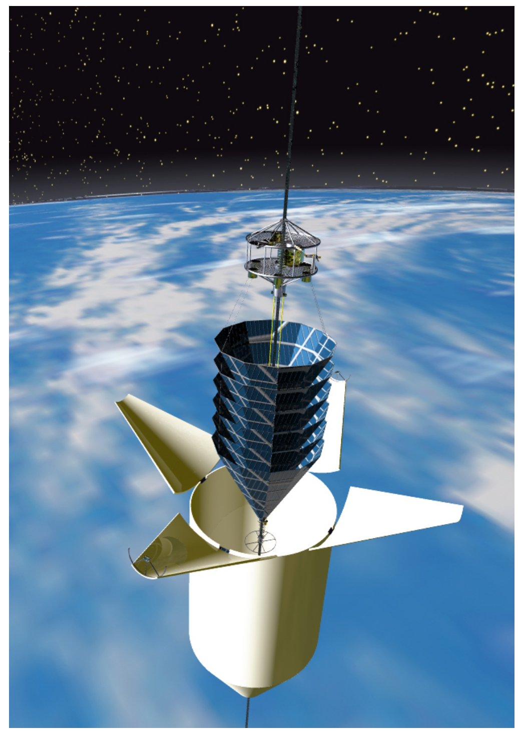


Figure 6.7, Box Protection Approach

Solution 2 - Spring Forward: Spring Forward has the advantage that the power is built in to the elasticity of the tether, which provides the propulsion. Effectively, the energy is stored when the Marine Node stretches the tether by reeling it in. An extension of 0.1% permits a length change of 100 km. A protective box will be necessary for the fragile solar panels. There will be variations in tension that will be transmitted up the tether all the way to the Apex Anchor. Happily, it was shown many years ago that there is natural damping of the resultant longitudinal oscillations. Of course, the tether must be strong enough to cope with these forces, including the weight of the protective box. At the required altitude, at or above 40 km, the protective box must remove itself from the tether climber to allow the climber to continue under its own power. The box must return to the surface.

Solution 3 - High Stage One (this concept is covered well in our ISEC study report entitled: "Design Considerations for the Multi-stage Space Elevator") This option for the space elevator Earth terminus takes the complexity of traveling through the atmosphere off the tether and places it on an Earth-based structure 30-50km high. To find the optimal altitude, much further work is needed on the solar panel design for the tether climbers. The stresses induced by the lower and upper atmospheres are dealt with by infrastructure based firmly on the Earth's surface. The space elevator is able to deal with the effects of Earth's turbulent atmosphere without adding substantially to the weight that has to be supported from geosynchronous orbit.

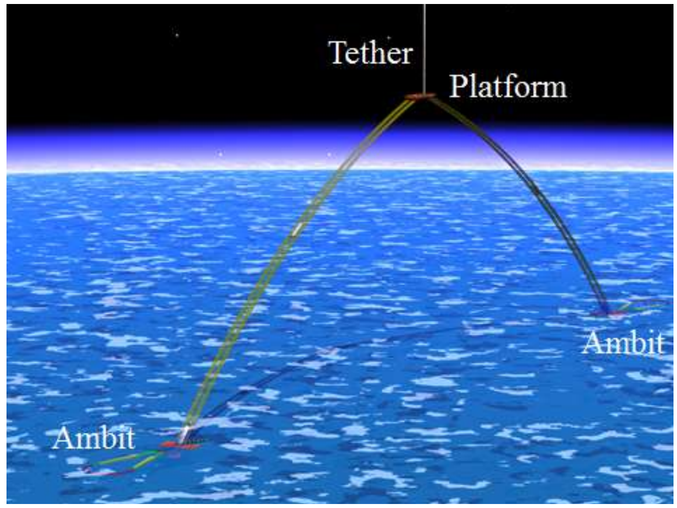


Figure 6.8, A loop with the platform at high altitude anchoring the tether

High Stage One achieves this by keeping the tether in and above the mesosphere. If the tether went down to the surface it would have to cope with wind pressure in the lower atmosphere. Using guy wires for stabilization or increasing the tension in the tether will cause strong variable forces that would have to be supported from the top. In addition, there are the hazards of ice and electric storms. The concept is to place the working end of the tether on a firm platform at altitude. This facility would be capable of supporting 3000 tons at 40km altitude with no forces on the tether. The Lofstrom Loop ensures stability of the platform at altitude and provides routine access from the ocean surface to 40km altitude using electric cars similar to a funicular used on mountains today. This transfer of hazards and forces from the lower portion of the space elevator infrastructure to the terrestrial based Lofstrom Loop simplifies the problem and reduces the mass requirement of the space elevator tether by a factor of 10. Once the platform has been established at 40km altitude and the logistics "train" has geared up, the space elevator infrastructure becomes safer and simpler. The basic principle is to create an upward levitation force on the high-altitude platform by using magnetic forces to change the direction of the momentum vectors of the rotors as they travel past. Friction is very low because the rotors travel in a vacuum inside the tubes and use a method of magnetic levitation employing permanent magnets stabilized by electromagnets under electronic control. A similar method of levitation is used in some machines, including vacuum pumps. Electronic controls can be built with extremely fast response times and low voltages, leading to very low power consumption and high reliability. To support a platform at 40 km altitude, the rotors need to travel at about 1.6 km/sec.

Conclusions: High Stage One simplifies the design of the tether and tether climbers by dealing with atmospheric hazards such as winds and ice independently and transmitting the forces down to the surface. It uses commonly available materials, including Kevlar. Magnetic levitation is a proven technology. Its use for dynamically supporting a structure is well researched but still immature, and so a prototyping and development schedule has been given to make it ready for use as part of the space elevator. Assuming successful tests, this is the preferred solution, but Box Protection and Spring Forward are also viable options for protecting the tether climbers from Earth's turbulent atmosphere.

6.5.2 Operating Safely inside An Environment of Space Debris:

Overview: The International Space Elevator Consortium's (ISEC) position has been well documented and discussed; it is called: Assured Survivability Approach for Space Debris. Space elevator research in a space debris environment was initiated in a 2010 ISEC study and reinforced in another study during 2020 - these are available at www.isec.org pdf-free:

- 2010 "Space Elevator Survivability, Space Debris Mitigation."
- 2020 "Today's Space Elevator Assured Survivability Approach for Space Debris."

The reports were developed after a full year of analyses by space debris and space systems experts. Since 2010, there have been events that have increased the growth of space debris. A second study was initiated in 2020 when another set of experts took a look at the situation and extrapolated across the arena to arrive at some significant results. The probability of conjunction numbers were calculated for two situations and compared to the initial study in 2010. The second study was based upon NASA supplied 2019 tracked debris data and a NASA extrapolation estimate of 2030 with projections of new satellite constellations. The approach, as discussed in the 2010 space debris report, is one where the volume of space around the Earth is shown to have a density of debris related to altitude zones. That initial report breaks out the zones, analyzes the information and derives conclusions. The collision probabilities are linear with respect to numbers of debris within the volume occupied by a 100,000 km of one-meter wide tether. The efforts focused on high debris density regions with identified zones between 200 and 2000 km altitudes. The report takes the density numbers, extrapolates the probabilities of collision and arrives at estimates. With discussions and calculations across three decades, the conclusion stays the same: for time periods - 2010, 2019 and 2030.

> "Space debris mitigation is an engineering and management problem with definable quantities such as density of debris and lengths/widths of targets."

Quick Summary of Results: The following list uses the 2010 words and replaces the numbers for 2030's extrapolation of densities, illustrating that space debris is a concern for all space systems working in LEO, less so for MEO and even less for GEO.

- The geosynchronous (and above) region was not a significant threat.
- The MEO region has similarly low probability of conjunction.
- The LEO region is the area of major concern with the following insights:
    - Untracked, small (<10 cm) debris will impact a Space Elevator in (LEO 200-2000 km), on the average, once every four days; and therefore, must be designed for appropriate impact velocities and energies.[19]

[19] Note: Numbers assumed the one meter cross section was always the calculated target area. As such the numbers are probably high by a factor of 2 (?) as the cross-sectional area is continuously varying with respect to the approach direction of the space debris, at some times there would be just the thickness of the tether material as the cross area target.

- Tracked debris will impact the total LEO segment (200 – 2000 km) once every 40 days or multiple times a year if no movement actions are taken.
- Tracked debris will only impact a single 60 km stretch of LEO space elevator, on the average, every seven years and every three years in the peak regions if no movement actions are taken.

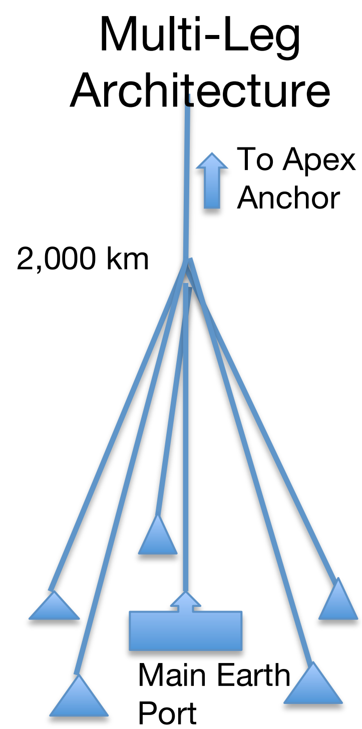


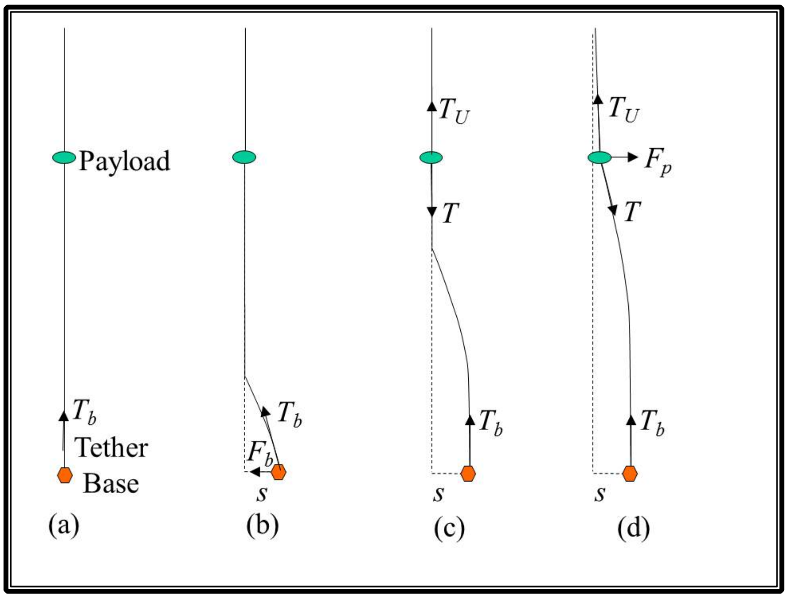
Figure 6.9, Multi-Leg Approach

Architectural Engineering Process: With the realization that there is much to do in architectural and engineering approaches to space debris mitigation, the following concepts have been assessed as first approximations:

1. Architectural and Engineering Design Inputs:
   - Multi-leg design: The multi-leg design is a concept where a principal leg is used for day-to-day operations of tether lift-offs and climbing. The other tethers are secondary in that they are there for backup in case of potential severance; however, they could be used to accomplish other missions such as low altitude hotel or scientific instrument placement. The shown concept has six legs joining at the 2,000 kms altitude - above dense LEO debris belts.
   - Designing the tether itself to survive small debris hits: The second approach is designing the tether to survive small debris (< 10 cm in diameter) "blow throughs." This has been discussed in many papers with the leading contender developed by Tethers Unlimited called the Hoyt Tether - a woven design spreading the tensile strength across multiple strands to ensure that if one is cut, the others share the load. Other tether designs, such as the use of multiple layers of a 2D material such as single crystal graphene, need to be examined and tested for the effects of ballistic penetrations of small objects with great energy. Curved ribbon one-meter wide with a woven design in the high debris threat region is to ensure all the non-tracked small space debris "blows through."
   - Include a repair tether climber that mends small holes or rips in tethers. Architecture trades show that having a repair tether climber going up and down repairing small holes or rips would extend the life of that tether. The current concept would put sensors on the front of each tether climber, inspecting as they go. Then a repair tether climber would be sent to the area of concern and patch or weave a "fix" for the tether for that location.
2. Operational Approaches:
   - Passive Approaches for Debris Mitigation include multi-leg design, varying tether design by altitude, and multiple parallel tethers for greater carrying capacity.

- Active Approach: Tether movement upon demand, on-orbit sentry satellite system, and approach for recovery from tether sever. The Space Elevator team has long cited the capability of the tether to move away from an impending collision. It is much like a simple "jump rope" movement, the movement generated by motion of the Earth Port's tether terminus with extra movement augmented by Reel in and Reel Out at either end. The instigation of "off-routine" motion of the tether can be accomplished with many techniques, such as:
  - Reel-in/out from GEO, Earth Port, and/or Apex Anchor
  - Slow down/speed up/stop and reverse direction of any of multiple tether climbers along the tether
  - Movement at Earth Port, GEO and/or Apex Anchor

Figure 6.10, Tether positions when swinging the base to avoid space debris[20]



- The Sentry Support: This concept is based upon the design of an electromagnetic tether satellite that can maneuver up, down, and across magnetic field lines to rendezvous with any approaching space debris. In this concept, tracked debris will be intercepted and removed. Debris headed for any portion of the Space Elevator will have intercept priority; but, if otherwise not encumbered by that priority the Sentry will gather and dispose of other space debris as a matter of course.[21] This Sentry System would then approach, attach itself, and move/deorbit the body. Multiple Sentries would be needed in different altitude ranges to ensure rapid responses.

3. Collaboration with Others:
   - Establish operational co-operations with Space Traffic Management organizations: This would include providing knowledge of space elevator locations (to include hourly locations of all 100,000 kilometer elements of the tether and projections for the next 24, 48, and 72 hours) and receiving

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[20] Knapman, John, "Design Concepts for the First 40 km - A Key Step for the Space Elevator,"

[21] Fitzgerald, M., "Space Elevator Architecture's Debris Mitigation Note #25," ISEC internal publications - available at www.isec.org, March 2019.

warnings and "heads-ups" of potential conjunctions from tracked debris or operational systems.

- Coordinate with owners of space assets (especially derelicts) at GEO: these can be used by space elevator operations for Apex Anchor mass or construction of needed facilities at GEO.
- Coordinate closely with organizations who will remove space debris. The elimination of major debris in orbit is critical to all travel and operations in space (this is a must; and, there are many people and organizations around the world who believe debris removal should be started as soon as possible to mitigate future challenges to normal spaceflight. This is NOT simply a space elevator issue; but, it is important for all spaceflight).
- Establish operational procedures to receive timely warnings and then respond to them: Establish a rapid capability for the Space Traffic Management System to instantly notify the space elevator community when there is a projected conjunction.
- The Space Elevator is a Catalyst for Change: Space debris is expected to be a part of space operations for most of this century. The real mitigation approach is the establishment of policy and actions that will prevent, and extensively reduce, creation of debris in the first place. The Space Elevator must become a catalyst to instigate more aggressive and active removal and mitigation of space debris.[22]

4. Timely Debris Alert & Warning:
   - ISEC foresees a close and interactive communication with the military Combined Space Operations Control Center - known familiarly as CSpOC. CSpOC is responsible for tracking thousands of debris pieces and providing orbital parameters for those pieces to operational space users. In addition, commercial capabilities have emerged which offer forming and formatting of that information to operationally satisfying their commercial customers.
   - Projecting future collisions is an important portion of the tasking for CSpOC, enabling timely warning of predicted conjunctions to be sent to the space elevator operations center. This timely warning would enable actions to move portions of the tether to avoid those predicted conjunctions.
   - ISEC expects that space elevator system operators will be able to depend upon a warning forecast within 72 hours of a convergence / close approach to a Space Elevator tether location. The Space Elevator team expects that CSpOC will hold a position as the Debris Mitigation chair in the Space Elevator Operations Center.

<u>Numerical Approach Taken:</u> The Executive Summary of the 2010 report stated: "To assess the risk to a space elevator, we have used the methodology from the 2001 International Academy of Astronautics (IAA) Position Paper on Orbital Debris[23]:

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[22] Fitzgerald, Michael, "Architecture Note #25, www.isec.org

[23] 2001 Position Paper On Orbital Debris, International Academy of Astronautics, 24.11.2000. download for free from www.isec.org

The probability (PC) that two items will collide in orbit is a function of the spatial density (SPD) of orbiting objects in a region, the average relative velocity (VR) between the objects in that region, the collision cross section (XC) of the scenario being considered, and the time (T) the object at risk is in the given region."

$$PC = 1 - e^{(-VR \times SPD \times XC \times T)}$$

Using this formula, we calculate the Probability of Collision for Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geosynchronous Orbit (GEO). Our focus is on LEO -- as fully two thirds of the threatening objects are in the 200-2000 km (LEO) regime. Our analyses show: Space Debris can be reduced to manageable levels with relatively modest design and operational "fixes."

Inside this numerical approach is an assessment of the number of collisions per segment (roughly 60 km long and 1 meter wide) in the various density regions. Some numbers are shown below as explanatory. A full understanding can be gained from 30 minutes of scanning the two reports. (free pdfs on isec.org) An estimate, leveraging the combined approaches, results in a total number of debris objects in space in 2030 of 38,000, as shown in Table 2.3. This results in a spread of debris population, as shown in Table 2.4.

***Item* (> 10 cm)**	***2010***	***2019***	***2030 Est.***	***Estimated with***
Debris Count by NASA	15,378	19,137	38,000 38,274	NASA numbers 2019 doubled

Table 6.1, Time population of Space Debris

<u>Detailed Results</u>: We laid out the conclusions from the 2010 report and extrapolate to 2019 and 2030. This was done in a linear manner as this is a straight forward projection.

Item	***2010***	***2019***	***2030 Est.***	***Comment***
Total Tracked Debris by NASA (2010 & 2019 measured, 2030 estimated)	15378	19137	38,000	Assume Internet constellations will add many space objects by 2030
Threats in GEO region (possible conjunction)	0.0026 per year	0.005 per year	0.01 per year	Good operational procedures a must.
Threat in MEO region (possible conjunction)	0.0003 per year	0.0006 per year	0.0012 per year	Good operational procedures a must.
Untracked, small (<10 cm) debris will impact a Space Elevator in (LEO	Once every ten days	Once every 7.5 days	Once every 4 days	Design for tether and movement planned to account for this -

200-2000 km), on the average;				with continuous repair[24]
Tracked debris will impact the total LEO segment (200 – 2000 km) if no actions are taken.	Once every 100 days or multiple times a year	Once every 75 days or several times a year	Once every 40 days or every two months or so	Note, this assumes there is no active movement of tracked objects or movement of the tether
Tracked debris will only impact a single 60 km stretch of LEO space elevator, on the average	Every 18 years with every 5 years in peak regions	Every 14 years with every 4 years in peak regions	Every 7 years with every 3 years in peak regions	Note, this assumes there is no active movement of tracked objects or movement of the tether

Table 6.2, Summary by Year and Altitude Region

As a result, the conclusion stays the same - for 2010, 2019 and 2030.

> "Space debris mitigation is an engineering problem with definable quantities such as density of debris and lengths/widths of targets. With proper knowledge and good operational procedures, the threat of space debris is not a show-stopper by any means. However, mitigation approaches must be accepted and implemented robustly."[25]

Recover from Severance: This is the lowest probability of occurrence event to plan for; but, it must be addressed systematically. The first assumption is the sever will occur at less that 2,000 km altitude - with the maximum likelihood at 800 km or 1,400 km altitude regions. These have the highest densities of space debris. The geosynchronous belt has less debris, a larger volume of operations, and slower moving debris (derelict satellites). In addition, the mid-orbit region has significantly less satellite debris and a huge volume. As such, this study calculated the numbers for those two regions that lead to the conclusion that this was not an issue. Of course, routine monitoring of the debris in those arenas must be conducted with mitigation approaches in place for quick responses. They will be studied later along with how to leverage derelict GEO satellites as mass for apex anchors. In addition, the major approach towards safe operations inside space debris environments is to have multiple legs below the 2,000 km altitude. The following discussion deals with a single leg being severed.

If there is a severance below 2,000 km, several operational procedures must be in place to ensure the safety of space elevator infrastructures. These ideas have been discussed but not studied. As such, they are listed here with recognition that analysis is a necessary action to be achieved within the near future:

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24 Repair of tether from small debris impacts is a must in the design, development and operational phases

25 Swan, P., R. Penny, C. Swan, "Space Elevator Survivability Space Debris Mitigation," Publisher Lulu.com, 2010.

1. Design an emergency response that unreels tether material from GEO downward when a large tension change warns that a severance has occurred.
2. Compensate at the Apex Anchor for any change in "center of mass" of the total system. This would probably result in release of some mass from the Apex Anchor commensurate with mass loss below.
3. Provide multiple leg infrastructure from 2,000 km enabling transfer of the main stress to a replacement "principal tether."

The threat from Space Debris can be reduced to manageable levels with relatively modest design and operational "fixes."

6.6 Summary: Developmental Progress: [from Swan 2020 pg 92]

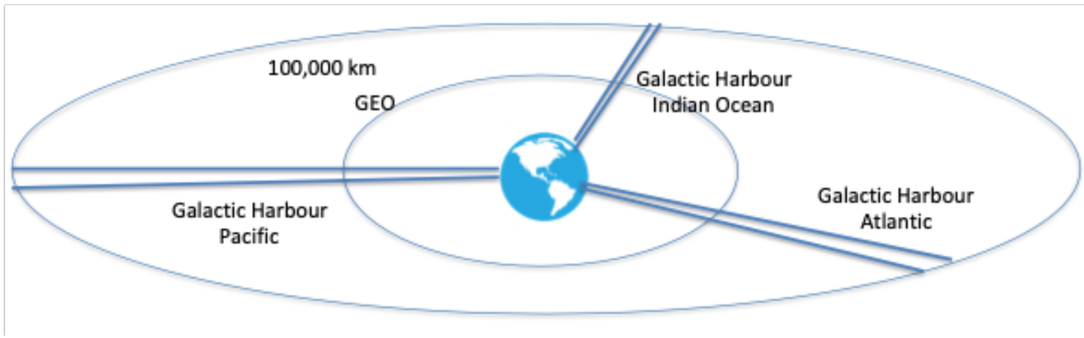
A "Sea State Change" has occurred within the developmental progress of Space Elevator concepts. Significant activities have occurred worldwide, as reflected in the International Academy of Astronautics (IAA) 2019 study report "A Road to the Space Elevator Era."[Swan 2019a] These engineering activities have led to a successful Preliminary Technological Readiness Assessment. This surfaced after multiple organizations accomplished major tasks:

- ISEC produced twelve year-long studies with resulting reports
- The IAA produced two study reports supporting the concept
- The Obayashi Corporation conducted an independent study that focused upon humans on the Space Elevator and massive movement of Space Solar Power satellites to GEO. [Ishikawa 2013]
- Internal ISEC assessments were provided by a series of Chief Architect's Notes. (see www.isec.org).
- The agendas of major international space agencies and private companies are aligning to target human presence and/or settlements on the Moon and Mars, thereby establishing demand pull.
- A recognition has occurred that the Space Elevator is a Green Road to space that will not only be carbon free, but can move massive tonnage to GEO and beyond, thus enabling Earth friendly missions previously considered too massive to begin.

Because of these achievements, many questions have been answered over the last ten years with respect to the readiness of Space Elevators. The position of ISEC is that the:

> Space Elevator development has gone beyond a preliminary technology readiness assessment and is ready to enter initial engineering validation testing -- leading to the establishment of needed capabilities. [Swan 019b]

Chapter Seven Story is Still being Written



In addition, we must dream big and see the Space Elevator of the future. As we discussed in our last study report, ISEC feels:

> "The Space Elevator story is still being written. The Apex Anchor is where the Space Elevator meets the Shoreline of Outer-Space and where the Transportation Story of the 21st Century meets the Final Frontier."

The Awakening

A NEW Space Transportation Paradigm has emerged. Ideas brought forward in a recent study report,[1] and this paper, are presented in clear and understandable ways, showing that a revolutionary concept is becoming realizable. The envisioned cooperative and collaborative operations between rockets and space elevators will benefit mankind into the next century. This architecture, with space elevators and rockets as a remarkable Earth to Space Transportation Infrastructure, provides logistics support to future missions throughout our solar system. This is a path to fully support interplanetary travel occurring by the second half of this century. This paper has highlighted the following realizations:

- Space Elevators can be accomplished because we now have a tether material
- Space Elevators ENABLE Interplanetary Missions
    - Fast Transit to Mars (as short as 61 days, with variations out to 400+)
    - Can release towards Mars EVERY day (no 26 month wait)
    - Can move massive amounts of cargo (170,000 MTs/year to GEO beyond)
- Space Elevators are Environmentally Friendly
    - Space Solar Power replaces 100s of coal power plants
    - No rocket exhaust to contribute to global warming
    - No additional space debris
    - Opens up remarkable commercial enterprises at Earth Ports, GEO Regions and beyond
- Offer to all future scientists
    - Any size science experiment
    - Any solar system destination
    - Releases every day towards multiple research destinations

How can this be possible? Simple - a working Space Elevator defeats gravity and the traditional rocket equation. Massive payloads to the Apex Anchor - raised by electricity - to be released at 7.76 km/sec towards destinations; daily, routinely, safely, and robustly all while being environmentally friendly. Combined with rocket architectures, future missions to GEO and beyond can be robustly supported.

Rockets to Open up the Moon and Mars
Space Elevators to supply and build up the colonies.

Pete Swan
9 August 2020

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[1] Swan, P., C. Swan, M. Fitzgerald, M. Peet, J. Torla, V. Hall, Space Elevators are the Transportation Story of the 21st Century, lulu.com, 2020.

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Appendix:

to be added as necessary