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Keynote: Jerome Pearson Memorial Lecture - Space Elevators as a Transformational Leap for Human Movement Off-Planet

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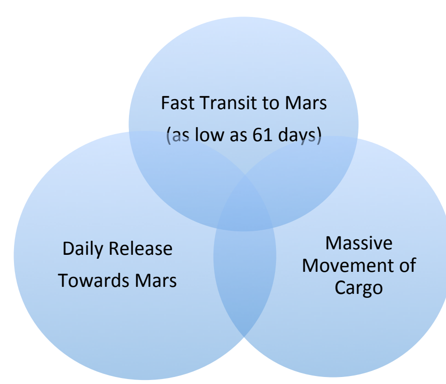
Abstract: This research has shown a Permanent Space Infrastructure would enable massive movement of cargo to GEO and beyond in a safe, environmentally friendly, inexpensive, daily and routine way – thus transforming the approach for humanity to escape Earth's gravity. How many dreams can come true when you can lift 30,000 tonnes to GEO and beyond per year – at initial operational capability (170,000 at full operational capability)? The restrictions of rocket launches are well understood; but, when you permanently beat gravity you: • enable Space Solar Power while supporting the Paris Accords • lift payloads as the Green Road to Space, helping to save our atmosphere • improve life on Earth with major accomplishments, in space • enable early completion of massive projects, such as lunar villages • shorten the time for delivery of 1,000,000 tonnes to Mars, and • enable early development of an L-5 settlement with millions of inhabitants. A Mars settlement will be used as an example: The most remarkable strengths of Space Elevators relate to being permanent transportation infrastructures. A recent study completed by Arizona State University and the International Space Elevator Consortium illuminated some remarkable capabilities about supporting settlements on Mars (as an example of off-planet development). This movement off planet includes Space Elevators': • Daily departures from the Apex Anchor towards Mars at great velocity (7.76 km/sec). • Support rapid interplanetary missions (Fastest transit is 61 days to Mars, with a range of travel times during the 26-month planetary dance). • Supply massive payloads daily (170,000 tonnes per year from three Galactic Harbours). • Enable carbon negative operations for deliveries to Mars • Exit the gravity well while avoiding the burden of the rocket equation. • And, accomplish this daily, routinely, inexpensively and carbon neutrally. Indeed, Space Elevators are the Transformational Leap For Movement Off-Planet.

1.0 Introduction: In early research with Arizona State University, the results lead to a study report that emphasized three recognizable impacts of using the Space Elevator Transportation System (SETS). This is reflected within the three circles of Figure 1. However, as the research has continued inside ISEC, several other remarkable Space Elevator characteristics have surfaced that reinforces the need for Space Elevators to support interplanetary missions.

1.1 Space Elevator Transportation System Strengths: From a historical transportation perspective, rockets have succeeded in launching spacecraft across our solar system. Their basic strengths have enabled successes on one hand, but held back our science and our quest to understand our solar system on the other hand. The delivery statistics of rockets are totally dependent upon Tsiolkovsky's rocket equation. The Saturn V rocket delivered only 0.5% of its launch pad mass to the surface of the moon. It was a spectacular and historic event; however, from a transportation view, it falls short of every other method of travel. Delivery to geosynchronous is somewhere around 2% of launch pad mass. The progress of rockets in the last ten years is remarkable with more reusability, more reliability, less cost and more launches. SpaceX just launched six times during the month of April 2022 and three times in 36 hours in June. However, the delivery statistics of rockets are roughly 4% to LEO, 2% to GEO and translunar and less than 1% to the surface of the Moon or Mars. The basic rocket equation eats up resources to escape from Earth's gravity well. As such, space elevators need to be there to enable spectacular missions for all our dreamers.

Figure 1: Significant Strengths Of Space Elevators



The transformation of space access will be similar to moving from small boats crossing a large river to a permanent infrastructure such as a bridge moving traffic daily, routinely, safely, inexpensively, and with little environmental impact. The permanent transportation infrastructures of space elevators will enable missions by leveraging their strengths:

- Daily, routinely, safely, inexpensively
- Transforming the economics towards an infrastructure with access to more valuable, lucrative, stable and reliable investments.
- Massive movement (Initial Operational Capability (IOC) at 30,000 tonnes/yr and Full Operational Capability (FOC) 170,000 tonnes/yr) [Swan, 2020]
- High velocity (starting at 7.76 km/sec at 100,000 altitude enables rapid transits to the Moon, Mars and beyond)
- As a Green Road to Space, it ensures environmentally neutral operations
- Reduction of the need for Rocket Fairing Design limitations
- Assembly at the Top of the Gravity Well

1.2 Vision of Space Elevators: As a starting point for this discussion, let us look at the concept of three competing commercial Galactic Harbours, each encompassing two space elevators. During initial operations, each space elevator will deliver 5,000 tonnes per year to GEO and beyond with daily lifts and releases from the Apex Anchor leading to 30,000 tonnes per year (5x6) delivery to GEO and beyond. (Note: humanity has only lifted approximated 26,000 tonnes to orbit in 65 years). This will become 170,000 tonnes when SETS are upgraded to their fully operational stages. Indeed, the vision is:

Space Elevators are the Green Road to Space where 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.

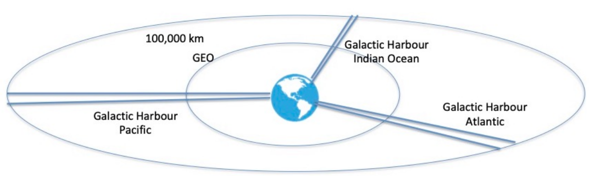


Figure 2, Galactic Harbour Vision

1.3 Demands of Dreamers: The reality of 2022 is that the global space industry is looking well beyond traditional space missions. The dreamers (near term customers) are aggressively developing capabilities as promised to their potential users that they will be there with tremendous capabilities. A few of these dreamers are:

- Mr. Musk has stated he predicts 100,000 settlers on Mars and 1,000,000 tonnes delivered to the surface.
- Mr. Bezos has initiated a large settlement in LEO, is competing on the NASA (commercial purchase) lunar lander, and is developing a highly reusable advanced rocket for movement off-planet. In addition, he is aligned with the National Space Society in their belief that space settlement will occur in the form of a rotating settlement at L-5 for 100,000 people with an estimated mass of 10,500,000 tonnes to the altitude of the Moon.
- NASA (and their Artemis partners) is aggressively planning on women and men on the Moon as well as a permanent lunar gateway in orbit around the Moon. A curious fact is they hardly ever mention the mass of their ventures.
- Similarly, China and Russia have a joint program to develop a research facility at the South Pole of the Moon. Once again, no one discusses the mass required from Earth's surface to succeed in this long duration mission.
- And then the most important (in our minds) is the early development of a space solar power constellation of satellites at GEO to significantly impact global warming and help countries reach net zero carbon by 2050. The latest designs of each satellite is for 2 GW of continuous transmission to the ground, times 600 satellites to replace coal plants as electricity generators. The problem that is not often discussed is the mass of each needed to be inserted into GEO – they range from 2,000 to 7,000 tonnes each.

This comes out to be a remarkable set of dreams, each with a heavy requirement for lift to GEO and beyond. (see Table 1) If you use 20 tonnes to GEO and Mars/Lunar/L-5 locations, the number of rocket launches is extraordinary. This summary is of recently discussed customer needs consistent with the current thrust to move off planet and stop global warming. Even one of these dreams is so large it would challenge all launch concepts on the table today. During a study by the International Academy of Astronautics entitled, "Space Elevators: An Assessment of the Technological Feasibility and the

Way Forward,"[1] current and near term needs for orbital delivery were identified (see Table 2).

Dreamer and Destination	***Mass to Destination (tonnes)***	***Number of Rocket Launches****
Mr. Musk and Mars	1,000,000	50,000
Mr. Bezos + NSS to L-5	10,500,000	210,000
NASA Moon and Gateway	? Significant	Significant number
China + Russia	? Significant	Significant number
Space Based Solar Powr GEO	3,000,000 +	150,000
		*At 20 tonnes to GEO and beyond

Table 1, Rough Estimate of Launches for each Dream

The below chart shows the spread of mass to orbit over a future time frame based upon the estimated growth of known and future missions. There is a considerable increase in mass needed to be launched to orbit over the next two decades. Then there are the dreamers adding more mass to orbit requirements.

2.0 SETS Transformational Strengths: The following sections will illuminate the seven transformational strengths and then show the direct applications (Impact) of each characteristic strength. When Galactic Harbours are operational, they will resemble train operations covering three oceans with pairs of Space Elevators, as shown in Figure 1. This set of six permanent transportation infrastructures will have the ability to enable customers' missions when using their inherent transformational strengths.

2.1 Strength One: *Daily, routinely, safely, and inexpensively*: The preliminary design of space elevators has shown there will be one climber initiating its departure from each Earth Port at sunrise each day with a seven day travel time to the GEO region. This enables logisticians to send a 20 tonne climber (14 tonnes are payload) up a space elevator daily, routinely, safely and inexpensively. This intermodal approach is to ensure the vertical lift capability is transparent as payloads originate in a city far away and travel to the Apex Anchor as one transportation infrastructure with the Earth Port transiting customers' packages from horizontal to vertical. In addition, with the extra velocity (identified in strength three) daily releases at an Apex Anchor can go to Mars any day of the year on different paths (some as quick as 61 days), thus eliminating the 26 month launch window required by planetary alignments for advanced rockets.

Impact upon Solar System missions: The routine aspect of a permanent space access infrastructure will be such an advantage when talking logistics or astronaut safety. The first is logisticians can now plan for "on time delivery" of supplies to anywhere in the solar system. There is no wait for alignment of the planets or the moon. The ability to attach a large rocket motor at the Apex Anchor ensures spacecraft can make it to their destinations with daily releases. Some will be rapid and some will take a little longer; but, this transportation infrastructure will ensure delivery on time to the user. Each Space Elevator will have train-like schedules with multiple destinations each day.

		Demand MT/yr		
	2031	2035	2040	2045
Space Solar Power	40000	70000	100000	130000
Nuclear Materials Disposal	12000	18000	24000	30000
Asteroid Mining	1000	2000	3000	5000
Interplanetary Flights	100	200	300	350
Innovative Missions to GEO	347	365	389	400
Colonization of Solar System	50	200	1000	5000
Marketing & Advertising	15	30	50	100
Sun Shades at L-1	5000	10000	5000	3000
Current GEO satellites + LEOs	347	365	389	400
Total MT	58859	101160	134128	174250

Table 2, Customer Demand [Tonnes per year[2]]

[1] Swan, P., Raitt, Swan, Penny, Knapman. International Academy of Astronautics Study Report, Space Elevators: An Assessment of the Technological Feasibility and the Way Forward, Virginia Edition Publishing Company, Science Deck (2013) ISBN-13: 978-2917761311

[2] Swan, P., Raitt, Swan, Penny, Knapman. International Academy of Astronautics Study Report, Space Elevators: An Assessment of the Technological Feasibility and the Way Forward, Virginia Edition Publishing Company, pg 280

2.2 SETS Strength Two: *Transforming the economics towards an infrastructure with access to more valuable, lucrative, stable and reliable investments:[3]* This strength is probably less subtle, but more important. This transformation results from the economic impacts of permanent space access infrastructures. This discussion is paraphrasing an article by two space elevator enthusiasts Kevin Barry and Eduardo Alfaro. [1] From the beginning of this century, the Space Elevator Community has played the rocket game – trying to show that it will be the least expensive transportation infrastructure. We CAN "beat" this low cost at so many levels; but, the discussion needs to be raised to another level by actually explaining that Space Elevators reach across economic growth arenas of enterprises across the solar system. The paper by Barry and Alfaro says, "With the current global trends favoring a burgeoning space economy, it is even more crucial than ever to develop a long-term sustainable economic overview for Space Elevators to accelerate the development of this megaproject."[4] In addition, they move the discussion from $/kg (which they call the language of rockets) to future key elements of economics and exchange of resources. Their argument is essential to the understanding of this issue. Their whole paper is worth reading to help transition from the early century's discussions towards what can be enabled by development of space elevators.

> "The economic paradigm of building Space Elevators needs to shift from a focus on cost to the consumer to focusing on its value to the investor. In infrastructure, this paradigm shift is especially important because the value of infrastructure comes from a reduction in transaction costs to increase the rate of utilization and thereby enhance economic productivity. To an investor, a Space Elevator is far more valuable as a departure point to the solar system and harbor for interplanetary trade than a business fighting to generate profit from selling ever-cheaper tickets to space. The true value of space is not based on merely reaching space, it is in what can be done once there. Space Elevators successfully address six of the seven major value streams for space development and creates a launching platform for extraction efforts (the final value stream) anywhere in the solar system."[5]

Impact upon Solar System missions: When placing economic "value proposition" approaches towards development and operations, the logical recognition of tremendous empowering characteristics dominate the statement: We must build space elevators as soon as possible! As the tether material will be available, the time is NOW. The Green Road to Space must be initiated as soon as possible. In addition, the strategic investment will pay dividends over decades because of economic development across the space arena. Space Elevators, and Galactic Harbour architectures, are no longer simple strings to space. They have become a transformational element in the movement off planet and a major thrust to control climate change. Their development has huge responsibilities to contribute significantly towards the health of the Earth and humanity's critical movement off planet. This new capability will be revolutionary in approach but evolutionary in scope.

2.3 SETS Strength Three: *Massive movement (30,000 tonnes/yr vs. approximately. 26,000 tonnes over 65 years by rockets)[6]:* As noted earlier, the ability to move 30,000 tonnes during initial operations will be revolutionary when compared to our rocket history. When considering that Space Elevator complexes will grow to a capacity of 170,000 tonnes per year, the belief is born that any mission can be fulfilled. There will be no limitations on the needs of customers as Space Elevators can deliver every day of the year to any location at GEO and/or beyond. Currently, our dreams beyond low Earth orbit are glorious; however, no one ever askes the dreamers "how much does it weigh?" Rocket restrictions are catastrophic when the realization dawns on the dreamer – "That is all we can deliver to my location and how infrequently?" A chart showing the natural growth (from two independent designs [3] and [4]) of Space Elevators' capacity is shown here.

[3] Barry, K., Eduardo Pineda Alfaro, "Changing the Economic Paradigm for Building a Space Elevator," 71st International Astronautical Congress, 2021, Dubai.
[4] Barry, K., Eduardo Pineda Alfaro, "Changing the Economic Paradigm for Building a Space Elevator," Acta Astronautica, to be published in 2022.
[5] Barry, K., Eduardo Pineda Alfaro, "Changing the Economic Paradigm for Building a Space Elevator," 71st International Astronautical Congress, 2021, Dubai.
[6] For development of these numbers, see Chapter 5 in: Swan, P, Swan C, Fitzgerald, M., Peet, M, Torla, J, Hall, V., "Space Elevators are the Transportation Story of the 21st Century," ISEC Study Report, www.lulu.com, 2020.

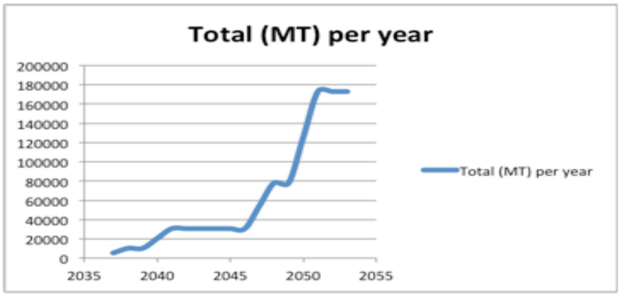


Figure 3: Massive Cargo Movement by Space Elevators[7] (MT is metric tonnes)

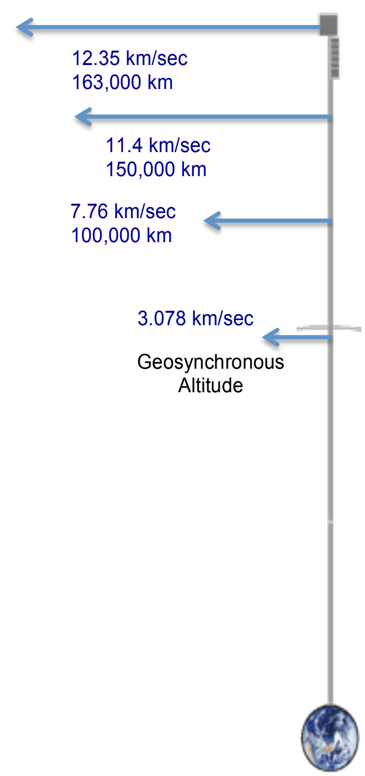
Impact upon Solar System missions: The phenomenal request by the customers for tens of thousands of tonnes of logistics to be delivered each year for their mission leads to a choice of advanced rockets and space elevator infrastructures empowering a collaborative and cooperative strategy. This Dual Space Access Strategy can enable Mr. Musk's million tonnes to Mars in roughly six years once SETS are in full operational mode. The comparable number was shown in the earlier chart with 50,000 launches to support his requirements. Even at 1,000 launches per year, it would take 50 years for SpaceX alone.

2.4 SETS Strength Four: *This Green Road to Space ensures environmentally neutral operations:* Space Elevators are environmentally neutral as they raise tether climbers using electrical energy from the sun. This enables climbers to transfer through the atmosphere without impacting it with combustion by-products. As the process is continuous with a single tether climber, there is no residual hardware left before its destination (space debris), especially in the Low Earth Orbit region. In addition to operating as a "green transportation infrastructure," it is also an enabler to many missions that can help stop global warming and climate change. Each of these would be missions (such as Space Solar Power and Earth Sunshades) that can stall global warming. These missions are discussed inside the 2021 ISEC 18-month study entitled: Space Elevators: The Green Road to Space. [2]

Impact upon Solar System missions: Recently, there have been a tremendous number of articles in significant magazines relating to research on the amount of carbon left in the upper atmosphere by so many rockets. If all 50,000 SpaceX launches occurred, the amount of tonnage of black carbon would be phenomenal with unknown effects. Yes, much of that can be improved by switching fuels, but there are still tremendous impacts inside the atmosphere when launching thousands of rockets through it. This can be helped by Space Elevators sharing the load of launching over the long run.

2.5 SETS Strength Five: *High velocity (starting at 7.76 km/sec at 100,000 km altitude) enables rapid transits:*[8] This strength results from the increase in velocity as tether climbers raise their payloads. The rotation of the Earth with a long "arm" instills tremendous velocity as altitude is gained. At GEO the velocity matches the orbit and then it increases rapidly as the altitude is increased. At the 100,000 km altitude of the Apex Anchor, the velocity is 7.76 km/sec, or enough to go beyond Mars with no extra propellent or reach Mars in as few as 61 days. As the height of the Apex Anchor is increased, the velocities allow the payload to reach within our solar system or escape it entirely.

Figure 4: Release Geometries



[7] Swan "Dual Space Access Strategy Minimizes the Rocket Equation," Space Renaissance International 3rd World Congress 2021 – Congress Theses, Final Resolution and Papers. Pg 254-255.

[8] Swan, P, Swan C, Fitzgerald, M., Peet, M, Torla, J, Hall, V., "Space Elevators are the Transportation Story of the 21st Century," ISEC Study Report, www.lulu.com, 2020.

Impact upon Solar System Missions:[9] [10] When thinking about the remarkable distances to our solar system planets, the initial velocity and timing of releases is extremely important. One significant problem is the ability to lift mass beyond our gravity well. This exiting of the sphere of influence (SOI) has been accomplished many times; but, usually its at a small velocity with expectations that the spacecraft would gain velocity as it uses gravity assists from other planets. The significantly increased velocity at the SOI when released from the space elevator enables so many more missions throughout our solar system just because of the initial conditions – high velocity. An example of that is the 61 days to Mars from the Apex Anchor. Two months instead of seven to nine months to Mars. During a joint study between Arizona State University and the International Space Elevator Consortium, researchers showed Space Elevators lend themselves to interplanetary missions as they transfer tremendous amounts of energy at release from an Apex Anchor. There have been other studies that have shown multiple methods for gaining much faster release velocities from the Apex Anchor, gaining even more capability to reach solar system destinations.[11,12]

2.6 SETS Strength Six: Reduction of the need for Rocket Fairing Design limitations: The beauty of a permanent transportation infrastructure, such as Space Elevators, is that cargo can move across distances efficiently, effectively, and with little effect on the cargo. This intermodal transportation technique is called containerizing. This concept is exceptional and is used for movement of supplies across the globe. There are roughly 45 million containers moving across the oceans, land, and air. With SETS, this concept transforms to vertical - containerized supplies on tether climbers. As such, the customer may load the container with any shape and any size satellite inside the standard TEU (twenty-foot equivalent unit) container. In addition, the gentle acceleration of electric climber motors on a tether will not disturb the product being moved. The lack of rockets' shake, rattle, and roll will simplify the design of satellites as well as storage and transportation requirements for transit to GEO and beyond. In comparison, loading the James Webb Telescope into its rocket faring, and then releasing into space, had 344 single point failure milestones to achieve deployment of the complex telescope and supporting infrastructure. This was after shaking it with tremendous vibrations and forces during both launch and release.

Impact upon Solar System missions: The ability to have flexible design criteria for space systems leaving the Apex Anchor is one of its strengths. Once the major segments of a large planetary science space system arrives at the Apex Anchor, it can be joined to large rocket motors and great scientific payloads such that it has tremendous reach across several scientific disciplines. With large batteries and robust spacecraft, scientific payloads can be designed towards any mission requirements. The raising of the segments of planetary mission satellites can take advantage of no "shake, rattle, and roll" and significantly less restrictions from rocket fairing size and shape.

2.7 SETS Strength Seven: Assembly at the Top of the Gravity Well: The idea is simple – raise payloads with solar energy to 100,000 km altitude and then assemble them in a robotic factory at the Apex Anchor. This leads to an operational capability which will release any size spacecraft, with appropriate rocket motors, to reach any planet in any inclination daily and safely – all while being environmentally safe. The concept relies upon the fact that the SETS operations will raise tether climber payloads of 14 tonnes to a rotating location with a potential energy of 100,000 km altitude and kinetic energy of 7.76 km/sec. Each payload can then be assembled into a much larger scientific mission spacecraft.

Impact upon Future Missions: The combination of massive energy given to any size scientific mission and assembled at the Apex Anchor leads to the realization that the universe opens up to anyone who operates a factory at the Apex Anchor. Can you image enabling scientists to dream of space systems that can be of any size and reach any solar system body with significant velocity? The enabling factor

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[9] Swan, P, Swan C, Fitzgerald, M., Peet, M, Torla, J, Hall, V., "Space Elevators are the Transportation Story of the 21st Century," ISEC Study Report, www.lulu.com, 2020.

[10] Torla, James and Matthew Peet, Optimization of Low Guel and Time-critical Interplanetary Transfers using Space Elevator Apex Anchor Release: Mars, Jupiter and Saturn," 69th International Astronautical Congress, 2019, Washington, D.C.

[11] Peet, Matthew, "The orbital mechanics of space elevator launch systems," Acta Astronautica, Jan 2021. Vol. 179:153-171.

[12] Knapman, John, Peter Swan, "Secondary Tethers," 72nd International Astronautical Congress, 2021, Dubai.

is a Space Elevator Transportation System with a robotic assembly factory at the Apex Anchor.

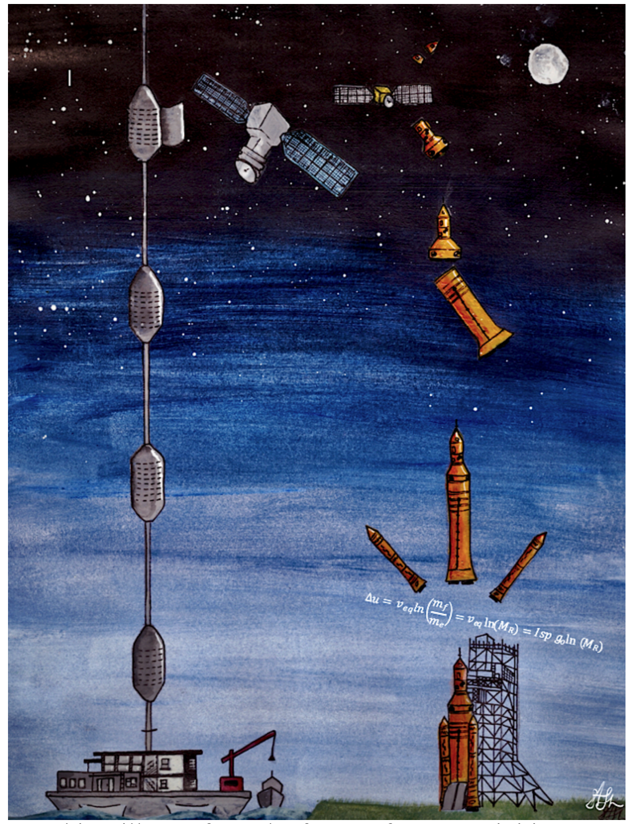

Figure 4, Dual Space Access Architecture
(Image by Amelia Stanton)

3.0 Reaching Orbit with Dual Space Access Architectures: When we look at the Moon and dream of spaceflight, we forget how extremely difficult it is 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 effort of great magnitude, we need to expand our vision of 'how to.' It would seem that the establishment of a robust infrastructure with reusable rockets and permanent Space Elevators working cooperatively must be developed. There are strengths and weaknesses of both components of this strategy with the combined purposes 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 the difficulty of fulfilling the dreams of the many is a monumental "reach." Expanding space access architectures to include Space Elevators will enable robust movement off-planet.

Four principle strengths of advanced rockets are:
1) rockets are successful today and great strides are forecast for the future, 2) reaching any orbit, and 3) rapid movement through radiation belts for people enables flights to the Moon and Mars. Transformational Space Elevator strengths will be compared to these rocket strengths while the difficulties of executing a Space Elevator developmental program are identified.

Rockets will Open up the Moon and Mars and initiate such dreams as Space Solar Power. Then Space Elevator Transportation Systems will leverage their ability to do the heavy lifting while their strengths will supply and grow the dreams of many.

4.0 Summary and Conclusion: The obvious emphasis from the above discussion is that the descriptive word is transformational. The implementation of Space Elevator Transportation Systems around the world will enable remarkable capabilities to move cargo massively and routinely. This will transform the future of space activities. Space elevator leadership must point out and emphasize to both the general public and project managers of visionary space activities that the modern day space elevator will be:

- Transformational
- A partner with rockets in a Dual Space Access Architecture
- Green: lifts payloads with electricity and enables Space Solar Power satellites to GEO with a timely schedule
- Closer than they think as SETS has entered engineering development
- A program for timely delivery of massive loads for development
- An economic boom as regions open up for commerce because of their routine, daily, and massive lift capabilities.

Space Elevators have many strengths; but, the most remarkable ones relate to their being permanent space transportation infrastructures. They will move massive cargo daily, routinely, safely and environmentally friendly. The level of impact on our future movement beyond LEO is obviously transformational. Dreams can be fulfilled.

References

[1] Barry, K., Eduardo Pineda Alfaro, “Changing the Economic Paradigm for Building a Space Elevator,” 71st International Astronautical Congress, 2021, Dubai.

[2] Eddy, et.al., "Space Elevators are the Green Road to Space," ISEC Report, Lulu Publishers, April 2021.

[3] Ishikawa, Yoji, The Space Elevator Construction Concept, Obayashi Corporation, IAC-13-D4.3.6.

[4] Swan, P., Raitt, Swan, Penny, Knapman. International Academy of Astronautics Study Report, Space Elevators: An Assessment of the Technological Feasibility and the Way Forward, Virginia Edition Publishing Company, Science Deck (2013) ISBN-13: 978-2917761311

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