IAC-23-D4.3.1

Keynote: Jerome Pearson Memorial Lecture - RESEARCH INTO CHARACTERISTICS OF A PERMANENT SPACE ACCESS TRANSPORTATION INFRASTRUCTURE

Peter A. Swan*, Cathy W. Swan*
*International Space Elevator Consortium, Phoenix Arizona, dr-swan@cox.net

Abstract: Research has shown Space Elevators' remarkable transformational capabilities as a permanent space access infrastructure dwarfs traditional space access approaches. Transportation infrastructures, such as trains, provide to the user: permanent; daily; routine; massive movement; safe; inexpensive; environmentally friendly; storage facilities at stations (ours are at GEO and the Apex Anchor); assembly and repair areas (above the massive gravity of Earth at GEO and Apex Anchor); rapid transit (in our case to the Moon/Mars); and, others. This paper will start discussions with the top-level transformational characteristics of a permanent space access transportation infrastructure – Space Elevators. This analysis at "a higher level" will enable discussions about the possibilities, instead of the technical difficulties in fulfilling their promises. The results of the International Space Elevator Consortium' (ISEC) Dual Space Access Architecture study show the characteristics lead to remarkable capabilities enabling both new and traditional missions. "As we build it – they will come!" This phrase has driven inventions and developments from the beginning of time. These types of statements are commercially powerful when a projected technology is going to transform the "way of doing business." These transformational leaps have enabled remarkable capabilities in communications, transportation, sports, business, and/or leisure. One potentially powerful transformation comes from Space Elevator electric tether climbers which can be seen as one of these game changers – no burning of rocket fuels inside our atmosphere or leaving of space debris in LEO. As Alfaro and Barry have stated: "The Industry must . . . develop a long-term sustainable economic overview for Space Elevators to accelerate the development of this megaproject."[1] As this is realized, investors will support the development of this transformational permanent space access transportation infrastructure. As we build it, they will come!

1.0 Introduction: The "Modern Day Space Elevator" terminology has been introduced to support the concept that space elevator development has matured through eight basic architectures. [2] This reflects the tremendous research conducted towards development of the permanent space transportation infrastructures and how they will support massive movement off-planet AND the health of our planet along the way. This paper will focus on three aspects of recent research:

- Tether/climber interface
- Tether material development
- Apex Anchor remarkable capabilities

One of the key elements in this series of research projects is that the International Space Elevator Consortium (ISEC) conducts 18 to 24 month studies which examine various aspects of the infrastructure (see studies at www.isec.org – pdf/free downloads). They have reached across the spectrum from the material to operations within the environment to interplanetary strengths. In addition, the ISEC has teams conducting parallel research of different topics to include:

- Dynamics and Simulation of System
- Green Road to Space
- Tether Climber design
- Apex Anchor design
- Tether material characteristics and laboratory results, as well as,
- Student research into interplanetary and interstellar capabilities

To place modern day space elevator characteristics within future missions to GEO and beyond, the ISEC team has projected massive movement of logistics to their destinations with multiple studies. To place the research to be discussed next in perspective, the basic capabilities of space elevators at their Initial Operational Capability (IOC) time period (estimated to be 2038) and Full Operational Capability (FOC) [3] are shown in the following Figure 1, as mass movement to GEO and beyond per year.

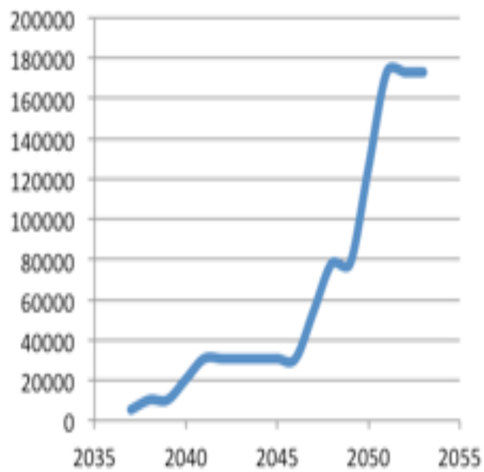

Figure 1: Total Mass to GEO/Beyond (tonnes)

The following three sets of research results will be expanded upon in future sections:

1.1 Space Elevator tether climbers can be built! The question assessed during this study entitled, "Climber-Tether Interface of the Space Elevator,"[4] resulted in the conclusion that the materials of today can build 20 tonne tether climbers which can raise themselves and have significant payloads.

1.2 Tether Material Rapidly moving from Laboratories: The same study [4] produced a result that was very reassuring to development. "The space elevator's tether could be built soon using lightweight, ultra-strong materials such as single crystal graphene, hexagonal boron nitride or carbon nanotubes." [5]

1.3 Space elevators newly recognized characteristics lead to transformational capabilities at the Apex Anchor. The combination of extreme velocity and the capability to assemble space systems above the gravity well opens up the solar system with interstellar reach to scientists and explorers.

2.0 Major Research Efforts: Over the last 15 years, the ISEC has conducted major studies to support the development of space elevators and their associated technologies. In addition, the International Academy of Astronautics (IAA) has conducted two 4-year long, multiple tens of authors, studies while the Obayashi Corporation conducted a definitive study in 2013. They are:

- Characteristics of Apex Anchor (2024 initiated)
- Dual Space Access Architecture (2023)
- Climber-Tether Interface of the Space Elevator (2022)
- Space Elevators are the Green Road to Space (2021)
- Space Elevators are the Transportation Story of the 21st Century (2020)
- Today's Space Elevator Assured Survivability Approach for Space Debris (2020)
- Today's Space Elevator, Status as of Fall 2019 (2019)
- Design Considerations for a Multi-Stage Space Elevator (2018)
- Design Considerations for a Software Space Elevator Simulator (2017)
- Design Considerations for Space Elevator Apex Anchor and GEO Node (2016)
- Design Considerations for a Space Elevator Earth Port (2015)
- Space Elevator Architectures and Roadmaps (2014)
- Design Considerations for a Space Elevator Tether Climber (2013)
- Space Elevator Concept of Operations (2012)
- Space Elevator Survivability, Space Debris Mitigation (2010)
- IAA - Space Elevators: An Assessment of the Technological Feasibility and the Way Forward (2014)
- IAA - The Road to the Space Elevator Era (2019)
- Obayashi Corporation - The Space Elevator Construction Concept (2013)

3.0 Tether Climber/Tether Interface Study: The latest ISEC study was entitled "Tether/Tether Climber Interface Study." [4] The abstract from their resulting paper, published within the Acta Astronautica series established the layout and conclusions. "A simple space elevator consists of a single tether extending well beyond geosynchronous altitude and a payload-carrying device which grips and climbs the tether. A friction-based, opposing wheel climber was judged most likely to be constructed with present-day technology and it appears that mass-production of the tether material is also within reach. The physical conditions at the interface between the climber wheels and tether determine first of all the possibility of climbing and then the design parameters of the tether. Conditions such as lifting torque, tensile, compressive and shear strength, friction, interface temperature, thermal conductivity and radiative cooling were examined and used to set minimum requirements for the tether material. Graphene superlaminate (GSL), consisting of layers of single crystal graphene, appears to be an excellent tether material with a sufficiently high tensile strength. An increase in its inter-layer cross-bonding and a larger mutual coefficient of friction with the climber wheel material would allow it to satisfy the climbing conditions. A final determination of the suitability of GSL requires the measurement of a number of, as yet unknown, material properties. A list of such measurements is proposed and a partial list of trade studies and iterations of design for the tether are provided." [5] From the initial conditions, consistent with the modern day space elevator, to the analyses of choice of tether gripper, size of tether climber, type of material, issues of the gripping (such as friction) the study significantly increased the knowledge of this puzzle – will an interface work between the advanced materials coming out of the laboratory today and the concept of tether climbers work together to enable construction and operations of tether climbers along a 100,000 km long tether. The specific conclusions were: [5]

- There is a need for further developments,
- State of the art for strong materials production has advance rapidly,
- It is likely advanced materials meeting the requirements of the space elevator will become available in the near future for testing,
- And, identification of several research areas should be emphasized with the purpose of building space elevators.

4.0 Latest Tether Material Analysis: A combination of research across the world and the need for a strong and long tether material for space elevators have yielded some very interesting conclusions. This recent study looking at the interface of the tether and the climber has also led to some very intriguing conclusions and recommend-dations for the research into these two-dimensional materials. Even in the early 2003 NASA Innovative Advanced Concepts (NAIC) study on the feasibility of space elevators, they recognized that tether characteristics would pace those developments. [6] Early requirements lead to the tensile strength of 100 GPa and capable of being produced in 100,000 km lengths. Over the last few years, the front runner materials have settled upon two-dimensional structures, such as graphene super laminant (GSL) and hexagonal boron nitride (hBN). The latest estimates of the strengths of these types of materials range from somewhere above 77 to 200 GPa. There are several corporations and laboratories testing and developing these materials around the world. While they have not been produced at the rates or shapes needed for space elevators, there are several products that have been very encouraging, such as a single crystal graphene sheet of 300 mm x 300 mm.

The next steps expected in the development of these remarkably strong materials involve heavy research into how to produce the material in quantities and shapes oriented to commercial applications. There is a process developing polycrystalline graphene (not single crystal yet) at the rate of 100,000 square meters per year. There is a new technique at General Graphene, in Knoxville Tennessee, that can produce single layer or in multiple (1, 5, 10, or 30) layers. In addition, there are two companies [LG Corporation & Charmgraphene] in South Korea that are producing roll-to-roll graphene at 1 or 2 meter per minute with one kilometer products. [7] Adrian Nixon, Editor of the Nixon Journal reporting on 2D materials, has recently shared his insight and has stated "It is not unreasonable to think that, as this graphene process continues apace, space elevator tether production could begin in five to ten years using graphene as its material." [7]

5.0 New Capabilities at Apex Anchor: During the research efforts inside ISEC, space elevators have developed transformational characteristics which greatly enhance their capability to fulfill the needs of future customers, focusing upon logistical support and moving great amounts of mass. These transportation characteristics were discussed extensively during the IAC-22 technical session on space elevators and are listed here to set the stage for surprising strengths not envisioned previously:

- Unmatched delivery efficiencies as well as daily, routine, safe, and inexpensive
- Unmatched massive movement (Initial Operational Capability (IOC) at 30,000 tonnes/yr with Full Operational Capability (FOC) 170,000 tonnes/yr),
- Unmatched 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 Rocket Fairing Design limitations
- Assembly at the Top of the Gravity Well
- Transforming the economics towards an infrastructure with access to more valuable, lucrative, stable and reliable investments.

An example case of Interplanetary Missions is used to illustrate the results of recent research into the Apex Anchor. Indeed, the combining of these characteristics for such demanding missions will surprise and please planetary scientists and their mission developers.

5.1 Assembly at the Top of the Gravity Well allows tremendous mass and efficiency: Unmatched delivery efficiencies will dominate the percentage of mass to the Apex Anchor. Space elevators will deliver 70% of the sea level lift mass to the Apex Anchor each day (vs rocket estimate of less than 2%). In addition, the capability to deliver 14 tonnes per day (at IOC), each day of the year enables so many missions not even conceived of today. The combination of these three characteristics enable any mission planer to assemble any size space system for release to anywhere in the solar system (or even towards interstellar).

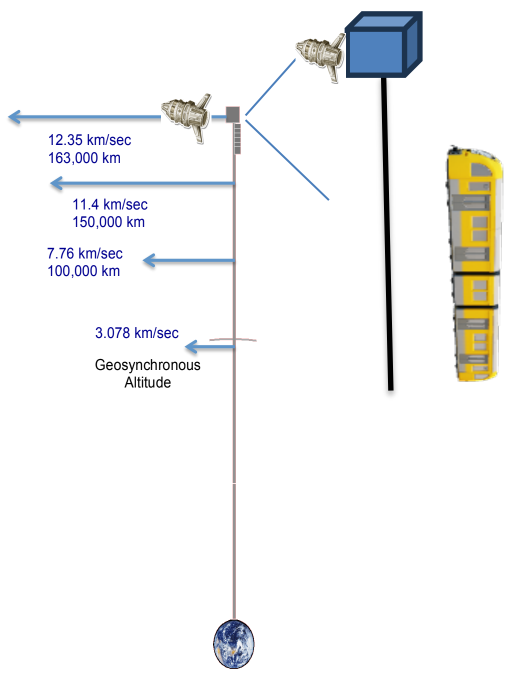

Figure 2: Assembly Above Gravity Well

5.2 Unmatched High Velocity: When spacecraft are released from an Apex Anchor at 100,000 km in altitude, the velocity is 7.76 km/sec – far faster than rockets can achieve. This results in a velocity that goes well beyond Mars with no additional rocket assist – except for landing at ones destination. If one were to build a 163,000 km tether, the velocity is sufficient to leave the solar system without rockets or gravity assists. These velocities are unmatched, and previously unconsidered, for interplanetary or interstellar missions.

5.3 Interplanetary Example: Can you imagine a huge space system rapidly leaving Earth for any of our solar system's planets – a dream of all planetary scientists [in months not decades] ? If a mission were structured leveraging the previously described characteristics of space elevators, the velocities would be remarkable while the assembly of any size space system at the Apex Anchor allows for revolutionary payloads. The example for this revolutionary capability is one of traveling towards our planets with a tremendous velocity and a huge space system with nuclear power and propulsion, massive scientific payloads and engineering support for a 10 year mission. This spacecraft would be assembled at an Apex Anchor with the estimate of 10,000 tonne satellite prepared for a long duration mission within our solar system. The next figure explains the resulting velocity after release from a high (163,000 km altitude) Apex Anchor on its way to planetary visitations. The components of the extreme velocity come from the following factors, as shown in Figure 3: Velocity Components:

- V_E - Earth's velocity with respect to the Sun (initial kick to rapidly escape the Sun) = 12.1 km/sec
- V_{AA} - Exit from the Apex Anchor = 12.35 km/sec
- V_{AV} - Additional velocity from special release approach = 10 km/sec [8]
- V_{GA} - Inherent velocity gained from a single gravity assist (could be multiple) = 15 km/sec
- V_{BSS} - Thus, resulting in a velocity towards their destinations: = 25.25 km/sec

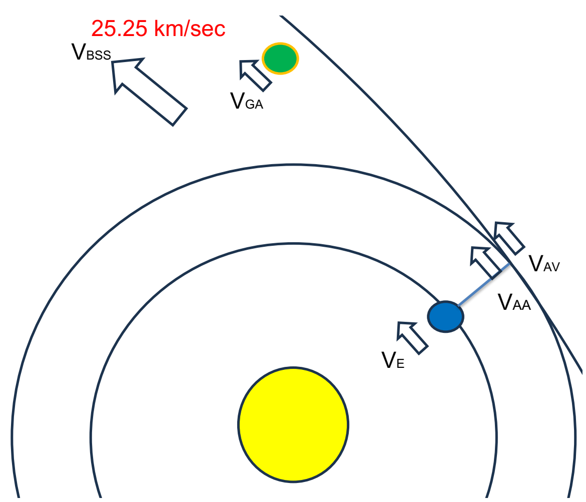

Figure 3: Figure 3: Velocity Components

This resulting velocity will result in great distances currently envisioned as decades long missions. The intriguing aspect that space scientists have not realized is that you "can bring it with you" with assembly at the Apex Anchor – nuclear propulsion, huge batteries, nuclear power, tremendous science payloads for numerous missions, and rocket motors to rendezvous or land systems on bodies both inside and outside of our solar system. As such, they may design missions such as 300 days to Neptune with a 10,000 tonne space system.

6.0 Conclusions: The revolutionary conclusions from recent research and understanding of the characteristics of Modern-Day Space Elevators leads to the following statements:

- Space elevator "tossed" mission spacecraft can reach the Moon and our planets with rapid transit, released almost every day, and can be huge when assembled at the Apex Anchor.
- Research has recently shown that we can build tether climbers which will move remarkable masses to GEO and beyond at 70% efficiency, every day while protecting our atmosphere as the green road to space.
- The extremely strong materials [two-dimensional, such as Super Laminate Graphene and Hexagonal Boron Nitride] allows "space elevator tether production to begin in five to ten years using graphene as its material." [7]

7.0 Recommendations for New Research: the significance of the strong enough and long enough tether material drives the necessity to emphasize this research and focus upon moving it out of the laboratory and into commercial production for all types of products – airplane wings, car bodies, as well as space elevators.

References:

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

[2] Raitt, David, "Space Elevator Architectures," Quest, Vol. 28, #1, 2021 pg 17-26.

[3] 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.

[4] Dennis H. Wright, Larry Bartoszek, A.J. Burke, David Dotson, Hassan El Chab, John Knapman, Martin Lades, Adrian Nixon, Paul W. Phister Jr., Peter Robinson, "Climber-Tether Interface of the Space Elevator," ISEC Study Report, www.lulu.com, 2023.

[5] Dennis H. Wright, Larry Bartoszek, A.J. Burke, David Dotson, Hassan El Chab, John Knapman, Martin Lades, Adrian Nixon, Paul W. Phister Jr., Peter Robinson, "Conditions at the interface between the space elevator tether and its climber," Acta Astronautica, 211 2023, pg 631-649.

[6] Edwards, B. The Space Elevator, NIAC Phase II Final Report, 2003

[7] Nixon, Adrian, John Knapman, Dennis Wright, "The Right Stuff," Spaceflight, Vol. 65, No 6, June 2023.

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