SPACE ELEVATOR ARCHITECTURES

By David Raitt

Abstract

The idea of a space elevator has captured the imagination of scientists and engineers (as well as writers and artists) for some 125 years and been the subject of studies by Russians, Americans, Europeans, and Japanese. The concept has been extensively refined and developed over the last few decades, and is currently conceived as a 100,000-km long, thin, strong ribbon or tether extending into space up which climbers will travel to release payloads in different orbits, as well as to the Moon, Mars, and elsewhere. Such a space elevator would be a tremendous transportation infrastructure affording massive fast-transit movement of cargo and supplies daily, safely and cheaply into space. This article describes the various insights gained from the published descriptions, studies, and experiments concerning the space elevator's concept and different elements, including its construction, engineering details, material, criteria, development, function, purpose, and operation. All these diverse insights have led to refinements and modifications of the various components making up the entire system (its architecture). To date, there have been eight such architectures (convergent rather than divergent) and a brief overview of each of these is provided.

Introduction

A space elevator is a tremendous transportation infrastructure leveraging the rotation of the Earth to raise payloads from the Earth's surface toward space and the solar system. The concept of a space elevator is simple and precisely as its name implies: a ground terminal on the Earth's surface tied to a space station by an enormously long thin tether or cable on which climber cars, powered by electricity (a choice or combination of sunlight and laser light projected from the ground), could deliver cargo, and eventually humans, to space. The orbital element would be located at roughly 36,000 kilometers (km) above the equator—i.e., geostationary orbit (GEO). As its name suggests, anything placed in this type of orbit remains perfectly in step with the Earth's rotation, maintaining a fixed position relative to a point on the planet's surface. The idea is that from a space station maintaining an exact position above the planet, a line is dropped that would eventually make contact with a ground terminal on the Earth's surface, in turn providing access to space, which would be entirely rocket free. Reaching outward from this space station, the line would also need to be extended to a distance of 100,000 km or more, where it would be attached to a counterweight, whose purpose would be to keep the entire system taut.

In a mature environment where space elevators are thriving in business and commerce, there would be several (probably up to 10) spread around the equator, each with a capability of lifting off greater than 20 metric tons of payload per day in the first instance, routinely and inexpensively. In time, with a thicker and stronger tether available, the space elevator capacity could be increased to lift as much as 100 metric tons every day. Advocates of a space elevator estimate that putting payloads into orbit using this method would cost a mere $100 per kilogram to GEO. By way of comparison, the average cost between 1970 and 2000 was $18,500, rising to NASA's figure of $54,000 per kilo when the Space Shuttle was in operation. Today, the cost per kilo of a SpaceX Falcon 9 launch to the *ISS* is currently some $2,700. It is worth pointing out that the cost of constructing a space elevator would be orders of magnitude less than any of the systems above.

In addition to launching payloads into orbit, the space elevator could also use its rotational motion to inject them into planetary transfer orbits—thus able to launch payloads to Mars, for example, once per day. This release could enable massive and fast transit movement of cargo and supplies daily. 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, though into space.

The idea of a space elevator has actually been around for some 125 years and since that time there have been various insights gained from the published descriptions concerning its concept and different elements, including its construction, engineering details, criteria, development, function, purpose, and operation. And all these diverse insights have led to refinements and modifications of the various components making up the entire system—its architecture.[1] This article gives a brief overview of these diverse space elevator architectures (now eight in number) made over the years to date.

The First Architecture

Russian Konstantin E. Tsiolkovsky is considered to be one of the fathers of rocketry, describing, as early as 1897, a formula to account for the change in a rocket's velocity as its mass continues to reduce while it expends fuel during flight. In his desire to gain access to space, Tsiolkovsky became interested in gravity, finding ways to simulate it as well as overcome it. His examination of the subject provided many hypotheses that he included in his numerous written works, including *Plan of Space Exploration* (1926); *The Space Rocket Trains* (1929); and *Album of Space Travels* (1932). However, it is in an earlier collection of essays, *Dreams of Earth and Sky* (Figure 1)[2] that there is what is considered to be the earliest abstract imagining of a space elevator.

In this piece, Tsiolkovsky speculated on a variety of methods as to how the pull of gravity could be diminished, shifted, or even reversed entirely given the application of a sufficient amount of external force. In explaining his ideas, Tsiolkovsky invited readers to imagine getting into a clay pot being spun on a potter's wheel, and how they would be able to stand fixed against the inner walls as the pot was being spun due to centripetal force, and the artificial gravity thus generated.

Tsiolkovsky took this idea further when he tried to calculate the centripetal force that would be required for one to be free of Earth's gravitational influence entirely. He suggested that if one were to be riding a train that ran full circle around the equator at a speed of 30,000 kph, the pull of gravity would be entirely reversed, and any passengers onboard would become attached to the ceiling. Tsiolkovsky contemplated the change in conditions if one were not trying to defeat gravity on the surface of the planet, where it is at its strongest, but rather using centripetal force at a point where gravity is significantly diminished—such as in space.

Figure 1. *Dreams of Earth and Sky*, Konstantin Tsiolkovsky.[2]

Having been inspired by the Eiffel Tower on a trip to Paris, Tsiolkovsky imagined even grander towers situated at the equator that stretched far into the heavens, at the top of which sat what he called "celestial castles." With Earth's gravity seeming to vanish entirely at what he measured to be a distance of 34,000 versts (roughly 36,000 km—or GEO) combined with the effects of the centripetal force provided by the rotation of the planet, he suggested that anyone standing inside his celestial castle would be looking up at the Earth, instead of down, as the pull of gravity would be effectively flipped.

Though the system he described in *Dreams of Earth and Sky* sounds incredibly familiar to what is now recognized as a space elevator—since his tower would be able to launch objects into orbit without a rocket—Tsiolkovsky was never acknowledged as the inventor of the space elevator because he never bothered to calculate the factors (e.g., the material for construction, line width, need for counterweight, how to transport to the top of the castle, etc.) required for his system's successful assembly and operation.

The Second Architecture

Some 65 years after Tsiolkovsky, another Russian, Yuri N. Artsutanov, came up with a more feasible scheme for building a space tower by using a geosynchronous satellite as the base from which to construct it. By using a counterweight, a cable would be lowered from geosynchronous orbit to the surface of the Earth while the counterweight was extended from the satellite away from Earth, keeping the center of gravity of the cable motionless relative to Earth. Artsutanov, unaware at the time of Tsiolkovsky's celestial castle concept, independently conceived of what he called a cosmic railway, the catalyst for which was an advancement in materials science that had recently been made in the United States. A super-strong material (tiny graphite whiskers) had been invented whose strength-to-weight ratio could theoretically allow for the construction of a cable up to 400 km in length without collapsing under its own weight. Artsutanov then came up with the idea of something even stronger: a fictitious super-material that could be used to extend a cable to an infinite length into the cosmos. That same material, as he imagined it, would serve as the rail in his cosmic railway.

His idea, "To the Cosmos by Electric Train," was published, with extensive detail, in the Russian tabloid *Komsomolskaya Pravda* on 31 July 1960 (Figure 2).[3] In this early depiction of what could be considered a space elevator Artsutanov criticized the rocket as too dangerous, having too lengthy a preparation process prior to each individual launch, and was thus an inefficient means of getting off the Earth. His notion of celestial moorings, or orbital spaceports, would allow for the docking and embarkation of large interplanetary vessels. These way stations would also employ smaller shuttles to ferry people to and from the planetary bodies they orbited. Artsutanov's concept envisioned that instead of using rockets to transport people up from the ground, travelers would use railways that would extend into the sky, tying the ground terminals on the surface directly to their orbital counterparts above.

In some respects his system was similar to that of Tsiolkovsky's in that the space elevator would have to be placed on the Earth's equator in order to utilize the centripetal force generated by the rotation of the planet. In explaining his concept, like Tsiolkovsky and his clay pot, Artsutanov drew a metaphor between a space station (located at 50,000–60,000 km away rather than the 36,000 km at GEO) revolving around the planet and a stone being swung around on the end of a string. He explained that just as the centripetal force allowed the string to remain taut, so would the same be true for his cosmic railway. As a completely new element in the design, Artsutanov's model also employed the spaceport to serve a dual purpose in that it would simultaneously function as the counterweight for the entire system, helping to keep the line taut, thereby preventing its collapse (things Tsiolkovsky didn't bother with, and still considered to be a necessity in the most recent models of space elevators).


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Figure 2. *To the Cosmos by Electric Train,"* Youri Artsutanov in *Komsomolskaya Pravda* on 31 July 1960.[3]

Artsutanov also noted that construction of the elevator would need to begin from a satellite placed at the geostationary point, where both the line being dropped to Earth and the one extending into space would need to be extruded simultaneously. He also drew attention to the need for the line connecting the spaceport to the Earth to exponentially increase in width as it was produced and slowly threaded toward the surface. However, he was cognizant of the fact that in 1960, there was no known physical substance whose strength-to-weight ratio could support such a structure as he envisaged. Artsutanov's elaborate engineering approach was sufficient to later label him as one of two independent co-inventors of the space elevator.

The Third Architecture

In 1975, American Jerome Pearson, finally managed to have published his article "The Orbital Tower: A Spacecraft Launcher Using the Earth's Rotational Energy."[4] It was a definitive paper that announced the entry of the space elevator to the scientific community at large and was a major step forward to bringing it to reality. Pearson resolved many issues with engineering calculations of tether strengths needed and approaches for deployment. His article was the first mathematical presentation of the space elevator and convinced scientists and engineers that such a grandiose alternative to rocketry was not only theoretically possible, but also the right way to go. Working independently, Pearson was unaware of Yuri Artsutanov's work 15 years earlier, but the pair later agreed to be known as the co-inventors of the space elevator (Figure 3).

Figure 3. Yuri Artsutanov (left) with Jerome Pearson.
Courtesy: Jerome Pearson

Pearson's work, in fact, made a leap beyond Artsutanov's ideas, and set the stage for the modern design for space elevators. He asked his readers to imagine a physical connection being made between a satellite at geostationary orbit and the Earth's surface below. He suggested that through the use of this connection, the deployment and return of satellites and spacecraft to and from the planet would be much safer, and require far less energy, which as a consequence, would also make them cheaper.

Like Artsutanov before him, Pearson recognized many of the finer mechanical details pertinent to the elevator's construction and operation—such as the need for assembly to begin at the geostationary point so that the increasing weight of the cable reaching toward the planet could be counteracted by a separate cable extending into space. But, whereas Artsutanov imagined his counterweight attached at a distance of 60,000 km, where it would double as a spaceport, Pearson fastened his at the much greater distance of 144,000 km. Pearson's design did not call for a true counterweight per se as he believed the sheer distance and mass of the line, and the outward force placed upon it by the spinning planet, would be sufficient to keep the structure standing.

Instead of interplanetary vessels departing from the station like ships from a harbor as proposed by his Russian counterpart, Pearson saw the elevator directly employing the inertia generated by the centrifugal movement of the rotating system to slingshot craft away from the planet. He estimated that anything launched in this manner from appropriate distances above the geostationary point would be able to reach as far out as Saturn without using any form of rocketry. This meant that traveling to Mars, for instance, would require no more energy than what was needed to reach geostationary orbit. If spacecraft were launched from even farther up the tower or extremely lengthy tether, Pearson theorized that the spacecraft would not require any self-propulsion at all to escape the solar system entirely.

Regarding the power that would be needed to reach geostationary orbit from the surface, Pearson, echoing Artsutanov, suggested that perhaps this energy could be supplied by a solar power station attached to the elevator system. Either that, or the energy could be captured from returning climbers as they descended the line back to Earth, generated via friction from braking that could be reabsorbed into the line. His system would harness the rotation of the Earth to launch craft into space, thereby eliminating the need for rocket propulsion, while also generating its own power.

Pearson backed up his explanations of a space elevator with countless numerical calculations by which he thoroughly accounted for every technical aspect of his elevator's design and operation, including the material of the line or tether, and its minimum strength-to-weight ratio. And, like Artsutanov, Pearson identified the need for the elevator's cable to be tapered in order to prevent the line from breaking under the enormous tension that would be placed on the system from both the downward pull of the planet and the counterweight being spun around it. Pearson also theorized that a suitable candidate might be found for the tether in perfect-crystal whiskers of graphite, a material whose tapering ratio would require that the cable be only 10 times larger in diameter at geostationary altitude than on the surface.

The Fourth Architecture

The conclusion from NASA's Advanced Space Infrastructure Workshop on Geostationary Orbiting Tether Space Elevator Concepts, which took place in

Huntsville, Alabama, in June 1999, was that the space elevator concept could become a reality and offer cheap transportation to geostationary orbit, dramatically lowering the cost of getting into space. The baseline plan considered at the workshop was to capture a carbonaceous chondrite asteroid and move it into a stable orbit around the Earth, then mine it for the necessary material to make a cable reaching down to the Earth. Such a space elevator, it was surmised, could be achieved within some 50 years.

Dr. Bradley Edwards was not satisfied with the end result that emanated from the 1999 workshop, nor with other concepts that had been put forward for space elevators. He believed that he could design a space elevator, albeit less robust, that could be built within 15 years with current technologies, assuming there would be steady advances in carbon nanotube (CNT) developments for the tether —a material he believed would be a game changer. Edwards gained funding from the NASA Institute for Advanced Concepts (NIAC) to work out his concept further and propose a space elevator infrastructure that would work in the near future.

In his NIAC Phase I and Phase II studies, Edwards spelled out his approach to a space elevator using a 100,000-km paper-thin ribbon made of carbon nanotubes. His vision included an initial spacecraft, ribbon production unit, climbers, power-beaming facility, anchor platform, debris-tracking system and the CNT ribbon stretching up into space, which would stand a greater chance of surviving impacts by meteors. Climbers would travel up the ribbon to release payloads into orbit at various points. Edwards expected that this international development would have a tremendous impact on society and industry within the next 20 or 30 years when the space elevator was completed and launch-to-orbit costs were reduced to around an anticipated $100/kg.[5]

Like his predecessors' architectures, Edwards showed how a space elevator offered the opportunity to break free of our complete dependence on rockets to get into space. By positioning the anchor in the ocean off the coast of Ecuador, weather and environmental hazards, as well as construction costs, could be reduced. CNT research and development efforts were progressing and plans were presented for construction of a first space elevator at an estimated cost of less than $10 billion.

Edwards' NIAC Phase II study answered many of the remaining questions thrown up in Phase I regarding the proposed design and scenarios and research began toward the construction of cable segments from carbon nanotube composites, and testing their general characteristics, such as resistance to meteor and atomic oxygen damage. Critical aspects of the space elevator design were further expanded, such as the anchor and power-beaming systems, cable production, environmental impact, the budget, and the major design trade-offs.[6]

The extensive work of Edwards, which reached a very large and receptive public, established the current baseline for space elevator infrastructures and demonstrated that the engineering could be accomplished in a reasonable time with reasonable resources. Subsequent space elevator architectures have been largely based on his work.

The Fifth Architecture

With the advantage of 10 years or so discussion about the space elevator's development and feasibility at conferences, in scholarly journals, challenges and games, as well as lab work, the International Academy of Astronautics (IAA) leveraged Edwards' design to further improve the concept and establish new approaches.

"Space Elevators: An Assessment of the Technological Feasibility and the Way Forward" was a five-year study first proposed in 2009 by Dr. Peter Swan and Dr. David Raitt to the IAA. The extensive research and work by a host of international experts and subsequent comments from peer reviewers were gathered into a lengthy study report.[7] The report addressed simple and complex issues that had been identified through the development of space elevator concepts over the last decade or so. Following a summary of the ideas put forward by Edwards and Eric A. Westling, the report then answered some basic questions about the feasibility of a space elevator infrastructure, namely what was a space elevator; why should it be developed; and could it be done?

Among the aspects considered in depth were the tether materials and climbers, as well as the end station infrastructure. Following a systems approach,[8] the study looked into the dynamics and deployment of the tether; the systems design for the environment and space debris; and also the operations concept. It also examined architectural and policy implications—giving a roadmap for development, legal and regulatory frameworks, market projections, and the financial perspective.

As with earlier architectures, it was recognized that the whole project, especially the projected price per kilogram, was dependent on a strong, lightweight material that would enable a 100,000-km space elevator tether. The principal issue was the production of suitable material at the strength, length, and perfection needed to achieve this. Almost all other issues surrounding each of the major segments had either been resolved in space before or were close to being space ready. Only the tether material was a high technological risk at this time.

The conclusions from the study fell into four distinct categories: (1) legal: the space elevator can be accomplished within today's arena; (2) technology: the space elevator "seems feasible"; (3) business: this megaproject will be successful for investors with a positive return on investment within 10 years after completion; and (4) cultural: this project will drive a renaissance on the surface of the Earth with its solutions to key problems, and stimulation of travel throughout the solar system, with inexpensive and routine access to GEO and beyond.

The Sixth Architecture

In parallel to the IAA study, in 2011 the Obayashi Corporation in Japan assembled a project team to develop an innovative approach to space elevators. Starting with Brad Edwards' design, they refined the concept from that initial set of assumptions and produced a construction concept in 2012. In 2013, the effort was reinforced with more research and development on the topic being conducted while working with governments, academia, and other industrial teams on joint research projects as the concept was further developed. One of the significant points was to focus on the cable dynamics and tether-climber interaction. The project was broken into three components to help direct the design efforts: designing the total space elevator architecture; analyzing the cable dynamics and its impact on strength requirements, and understanding how to accomplish the construction of a total system of systems.[9]

Regarding the design of the total space elevator architecture, the design of the concept included resolving all necessary components including cable, stations, and climbers. The cable, made of carbon nanotubes, was to have a length of 96,000 km with multiple locations along the tether. The length was chosen based on three criteria: first, the cable should not resonate with periods of tidal forces from the Sun and Moon; second, it had to be long enough to send spacecraft to as many planets as possible in the solar system; and third, the overall length of the cable should be a multiple of the interval of periodically ascending climbers. In their concept, Obayashi assumed the tensile strength of the cable to be 150 GPa with a safety factor of two. The climber, which was not designed in detail in the study, was assumed to weigh 100 metric tons.

The basic design of the tether started with the Edwards number of 150 GPa tensile strength requirement. This included a slight taper ratio and defined two tethers per cable. This dual cable arrangement was to provide a larger safety factor as Obayashi identified the transport of humans as a priority. The Obayashi concept was designed based on the numerical results of the dynamics of the cable, and the various forces, such as Earth's gravitation, centrifugal, Coriolis, elastic and air resistance were all taken into consideration.

For the construction process Obayashi basically followed Edwards, but modified the details. The process mainly comprised the construction of the Earth Port, the cable, and the stations along the way. The construction of the cable includes the launch of an initial cable to GEO, the deployment of the cable from GEO to Earth, and the reinforcement of the cable with ascending climbers. Their analysis concluded that the reinforcement or thickening of the cable required 510 climbers and would take 18 years.

There was much design consideration during the development of the Earth Port concept, with attention being paid to the platform, the climber car size and weight, and the energy to be supplied. The construction approach and timeline matched the Edwards layout, and there was also a very good parallel with the development of the IAA study architecture. However, the development of the extra strong cable and double tether arrangement would require a longer development cycle and construction time. The Obayashi estimate was that operations would begin somewhere around 2050 with placement of the initial single string tether in the 2030 time period. The development time between those dates reflected the complexity of building up the tether cable design from the initially deployed cable. Basically, Obayashi's set of assumptions for ita study established stricter requirements and resulted in longer developments with increased payload capacity, partly because the focus was movement of humans and massive loads to GEO and beyond.

The Seventh Architecture

A follow-on five-year IAA study, "Road to Space Elevator Era," chaired by Akira Tsuchida and co-chaired by Dr. Peter Swan and Dr. David Raitt, kicked off its activities in 2014 with the aim of accomplishing the development of the unique space transportation system of the future, by means of more international cooperation stretching across the science and systems development community. To achieve this, projects were identified that could be accomplished in the near future leading to risk reduction and engineering enhancements. These included on-orbit verification projects such as utilization of the *International Space Station* characteristics, promotion of space technology spin-out into industrial application, and execution of precursor mission, leveraging current technologies to demonstrate space elevator prototypes.[10]

It was the intention of the IAA Study Group to support any activities in connection with the topic of space elevators and to bring within the reach of every country the opportunity to understand the potential, design approach, and benefits/issues with a developmental program. The exploitation of space elevators to initiate space-based solar power was an initial focus that would demonstrate the possibilities available to humanity. The study was completed with inputs from almost 50 contributors and leaped ahead of previous architectures to include: the functional requirements and technological needs of each major segment of the system; the critical technologies risk identification plus the validation and verification of those technologies; as well as solar energy to drive the tether climbers. It also recognized that the search for a tether material had moved on from carbon nanotubes toward new revolutionary two-dimensional materials such as single crystal graphene or boron nitride crystals. The study also introduced the concept of the Galactic Harbour, developed within the International Space Elevator Consortium (ISEC), as a growth to a future architecture.[11]

Galactic Harbour is a new term representing the multiple independent space elevator segments previously identified that make up the concept (such as the Earth Port, Tether, Tether Climbers, GEO Node, Apex Anchor, Mars Gate, and so on). In this new architecture, all these segments have also been named and defined in more detail. Thus we have, for instance, the Earth Port, which is a complex located at the Earth terminus of the tether to support its functions, and along with it the Earth Port Region; the Apex Anchor is a complex of activity located at the end of the space elevator providing counterweight stability, and there is also its Apex Anchor Region; and the Mars Gate, which is the release point on the tether (at roughly 57,000-km altitude) for orbits to Mars. A complete list of the new terminology can be found at https://www.isec.org/lexicon.

The Galactic Harbour can be defined as continuous operations of the space elevator as the Galactic Harbour moves customer payloads on multiple space elevators from the entry ports to exit ports. These locations would most logically be the Earth Port, where the customers have their payloads loaded on space elevators and then the release points (e.g., the GEO node or Moon Gate) are at varying altitudes in accordance with the desires of the customer.

The Galactic Harbour offers major strengths through the combination of the necessary space elevator transportation infrastructure with commercial or business enterprises which will develop naturally within. The resulting vision of Galactic Harbour shows multiple locations around the equator leading to six or more space elevators inside three Galactic Harbours supporting, as a principal mission, interplanetary logistical support. Any of the Galactic Harbours will be up to 100,000-km high for payloads to be released at Apex Anchors.

In essence, the Galactic Harbour is visualized as an Earth Port, at the bottom end of the tether, with a complex of platforms performing different functions; two tethers going up from two Earth Port tether termini; an Apex Anchor—the smart counterweight at the far end (100,000-km altitude) of each tether and used to control the dynamics of the tether termini; up to seven tether climbers on each tether below GEO—with three climbers beyond GEO going to the Apex Anchor or release point for Mars or the Moon; and GEO Node region centers—considered as free-floating multipurpose spaceports with multiple functions (such as refueling/servicing/construction, tug boats, power generation, communications, etc.)

The Galactic Harbour would then be the area or region encompassing the Earth Port covering the ocean where incoming and outgoing ships/helicopters/airplanes operate and stretching up in a cylindrical shape to include tethers and other aspects out toward Apex Anchors (Figure 4). A Space Elevator Transportation System will then be the core priority construction activity and its success will be the foundation of the Space Elevator Enterprise.

The Galactic Harbour is seen as the unification of transportation and enterprise, with businesses flourishing as the movement of goods becomes routine. This would enable a tremendous expansion of our ability to support operational satellites with such functions as refueling, repair, large-scale assembly, and refurbishment. One industry that is hoping for early space elevator success is the space-based power arena, which needs large satellites in geostationary orbit for collection and transmission of power to the Earth's surface. Easy and inexpensive delivery to GEO would then lead to assembly, checkout, and operations of massive satellites. Furthermore, a few years down the road, it would be the transport of people to space via the space elevator. This full operational capability will lead to tremendous growth of business at all the regions, especially across the GEO region.

The Eighth Architecture

Although the idea of incorporating the Galactic Harbour into the space elevator architecture is rather recent and shows a high degree of maturity into the overall concept, newer developments have necessitated a re-evaluation of the overall strategy for bringing the space elevator to fruition. Hence the current thinking within the space elevator community is of a dual or combined architecture with rocketry to reduce the shortfalls of each by combining the strengths of each.[12]

Such a Compatible Space Access Architecture would enable human migration off-planet robustly and safely. One significant conclusion is that using the strengths of both parts of this architecture enable so much more than the individual parts or segments (Figure 5).

As noted, a space elevator has the tremendous ability to move massive payloads, daily, routinely, inexpensively, ecologically sound, and safely off-planet. Each of the major regions inside the "main channel" of the Galactic Harbour will expand as needed to handle this daily and massive core business, i.e., the transportation of goods. Hitherto, the assumption has been that the space elevator would obviate the need for rockets; however, now that we, or at least private individuals and companies, have decided to go back to the Moon and on to Mars, we need to expand our vision of how we do this. There is little doubt that rockets will still fall short and not be up to the expected demand. Elon Musk, with his planned colony on Mars, has said that he needs one million metric tons of cargo delivered to Mars to build his outpost. Another customer requirement is for solar power satellites and the prediction of what is needed to supply 12 percent of the electricity demand for customer by 2060. This mission to eliminate hundreds of coal-burning plants is said to require five million metric tons of cargo taken to geosynchronous orbit. A third mission referenced in research is a Moon Village, which requires some 500,000 metric tons delivered to the lunar surface.[13] Given the current launch capacities of rockets and the number of launches able to be undertaken per day and taking into account the available launch windows, that would likely take well over 100 years at best and require some 200,000 launches through the atmosphere to fulfill Musk's goal.

If, as Jeff Bezos has stated, that a road to space has to be built, then it would seem that the establishment of a more robust infrastructure with reusable rockets and permanent space elevators must be developed. The unique characteristics of space elevators—which would already be a multilane highway—with a rapidly moving Apex Anchor enable remarkable opportunities for off-planet missions. This combination of three major strengths (massive movement of mission support equipment, a tremendous opening up of launch windows, and far shorter travel times) would ensure constant support to missions beyond geosynchronous altitude. The daily release of payloads toward Mars (and other interplanetary destinations) from the Apex Anchor imparts tremendous velocity with very little drag from Earth's gravity. Enough velocity would be provided to reach the Moon in 10 hours. Periodic fast transit to Mars would lower the time from some six months or so at present to as low as 61 days at best with many transits taking only 80-100 days. In addition, the launch window for rockets to Mars open only once every 26 months, could be overcome by multiple launches every week toward Mars. Adding these two characteristics of space elevators to the routine, daily, and massive movement of cargo (170,000 metric tons per year when the system is mature) ensures that human missions off-planet will always have the supplies needed to prosper and grow.

Conclusion

In 1960, Eddie Cochran released his great song "Three Steps to Heaven." This article has shown that, in fact, there are several more steps than he considered necessary to bring to reality a "highway to heaven" in the form of a space elevator. The steps are viewed as essentially different architectures—each adding a bit more to the one before. The first step undertaken was in the very late 19th century when Konstantin Tsiolkovsky looked at the Eiffel Tower and envisioned something built up toward geosynchronous orbit. The mid-20th century saw two further steps or architectures—first with Yuri Artsutanov presenting a realistic approach on how to achieve Tsiolkovsky's vision by basing a string centered at geosynchronous altitude; then with Jerome Pearson resolving many of the issues thrown up by Tsiolkovsky and Artsutanov with engineering calculations of tether strengths needed and approaches for deployment. These early approaches set the stage for what can be considered as the modern design for space elevators.

The first two or three years of the 21st century saw Brad Edwards establish the baseline for space elevator infrastructures—including location, dynamics, and tether material. Edwards established that the engineering could be accomplished in a reasonable time with available resources, save for the tether material. The International Academy of Astronautics then took Edwards' design a step further and made several additions based on new research and developments. Meanwhile in Japan, the Obayashi Corporation, also taking Edward's design, released a new version of the space elevator architecture—basing its assumptions on stricter requirements (since human crews were involved), longer development time, and increased payload

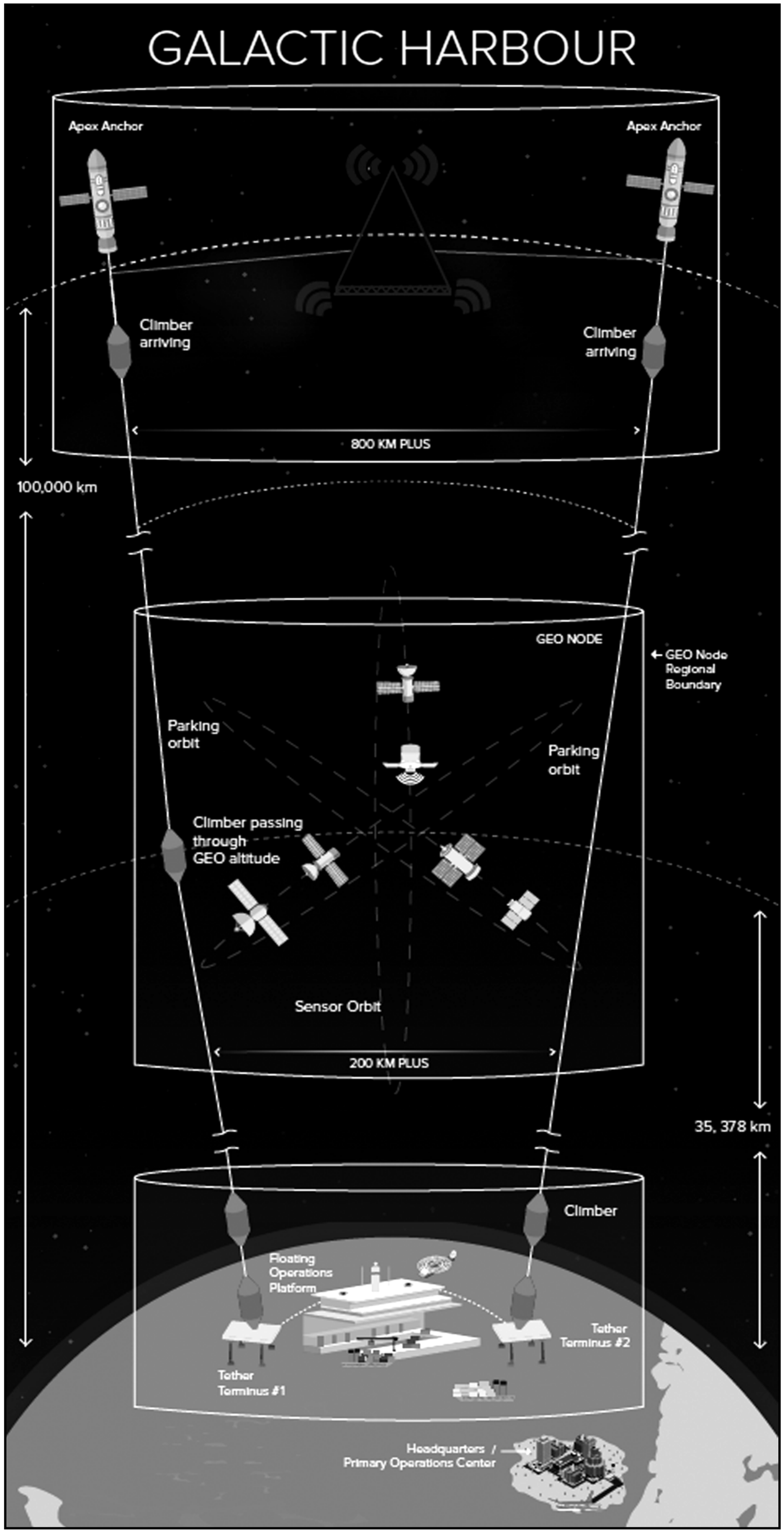

Figure 4. Galactic Harbour. Credit: ISEC

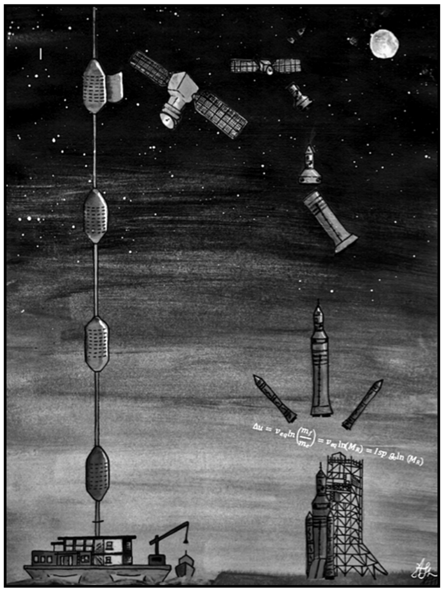

Figure 5. Combined architectures.
Credit: Amelia Stanton

capacity. Then, a follow-on study by the IAA took everything another significant step further with not only more attention to climber power and a new tether material, but also with the introduction of the concept of a Galactic Harbour, which showed that there had to be a unification of the actual transportation infrastructure (the elevator itself) and the commercial enterprise (the movement of cargo spaceships) that would take place within it.

The latest architecture takes the logical approach of combining both the architectures of space elevators and that of rockets of the future to ensure that the best of each system is leveraged to create what both parties require. This insight informs that the bottom line for access to Mars and beyond should consist of a combined or dual architecture comprising both rockets and space elevators. Rockets should be emphasized for the movement of people since they have tremendous support for LEO and MEO destinations; while space elevators should be leveraged for GEO and beyond due to their ability to deliver huge volumes of cargo and equipment to the Moon and Mars rapidly and securely. In essence, the space elevator community's vision, as promulgated under the auspices of the International Space Elevator Consortium (which has released a number of study reports on space elevator architectures and has a very full bibliography of references (see https://www.isec.org) is now converging with Blue Origin and others, namely millions of people living and working off planet productively. To this end, we need to build Jeff Bezos' "road to space." The space elevator has been shown to beat the rocket equation, and accordingly the space elevator and rocket communities should join forces to further the concept of a Dual Space Access Architecture. This would lead to a true multi-lane road to space capable of meeting all demands

About the Author

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Notes

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