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SPACE ELEVATORS ENTERING ENGINEERING DEVELOPMENT - NOW

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Abstract

The Space Elevator community has developed the necessary body of knowledge sufficient for the initiation of a Space Elevator development program. With the publishing of 16 technical studies (2 IAA, 13 ISEC, 1 Obayashi) we believe the implementation of a Space Elevator is now necessary to support humanity's needs and dreams. We can make the bold statement -

> *We are ready to initiate a mega-project, called the Space Elevator - 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 Humankind, as the green road to space.*

The process of Architectural Engineering, which focuses on major system development, is relatively new in the space arena. This paper looks at Architectural Engineering as a discipline and shows its strengths for producing developmental roadmaps. Space Elevators are shown as being in a sequence, or flow, of development. This explains how the design of Space Elevators has moved past the preliminary technological readiness assessment and is ready to initiate segment level testing towards engineering validations. 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 with traditional approaches. • Second: The situation has altered in the Space Elevator developmental status. We now have a material that can be used for the tether and is long enough and strong enough. Phase two 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, and baseline operations performance.

1.0 Preface and Introduction: In the last 19 years, there have been 16 study reports assessing the progress of the Space Elevator program. There were two International Academy of Astronautics studies, thirteen International Space Elevator Consortium studies, and one corporate study conducted by Obayashi summarizing the various critical aspects of Space Elevator development. The first chart shows these studies and where they reside. The key elements of these completed studies is that they all took the complexities of a mega-project development and evaluated them in engineering terminology. The IAA study, "Space Elevator: An Assessment of the Technological Feasibility and the Way Forward," resulted in the conclusion that the Space Elevator is feasible with the recognition that the tether material was the "long pole in the tent." Now that the 2D material revolution is occurring – there is a material for the Space Elevator tether that will be long enough and strong enough by the point in development when it is needed for testing. This recognition that the program could be initiated encouraged the International Space Elevator Consortium to focus upon this conclusion and break the process down into sequences and phases of development. The Study report entitled Space Elevator Architectures and Roadmaps laid out the process and path forward to development of the permanent space access architecture. This process has been followed since that time period and has led to several conclusions:

- The Space Elevator is Closer than you think
- The tether material has been shown to be available in time for first operations
- There is an engineering roadmap to follow to fulfill the vision

Table 1: Space Elevator Study Reports

2021	Design Considerations for the Space Elevator Climber-Tether Interface - in progress
2021	Space Elevators are the Green Road to Space
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

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

- The Space Elevator will be a permanent transportation infrastructure tying the Earth to Geosynchronous and beyond by moving heavy cargo daily, routinely, inexpensively, safely and environmentally friendly.

The other reports from these various studies support the conclusion that indeed Space Elevators are ready to proceed into Engineering Validation phase of the program.

1.2 Architecture and Roadmap:

The first IAA study showed the way forward with an engineering plan. The conclusions from that report[1] are:

- The Space Elevator appears feasible, with the realization that risks must be mitigated through technological progress.
- A Space Elevator infrastructure will be achievable through a major global enterprise.

In addition, the ISEC study entitled Space Elevator Architecture and Roadmaps[2] recommends:

1. Initiate the development, test and validation of a "high fidelity model" representing a space elevator system.
2. Endorse the current ISEC Research Plan [see at www.isec.org].
3. Engage in an active program to address the top five Grand Challenges discussed in this study report:
4. High Fidelity Dynamics Modeling of the Tether as a system from the Marine Node to the Apex Anchor with GEO Node and tether climbers.
5. Understand, measure, and improve the tensile strength of new materials with promise as future space elevator tethers.

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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 Fitzgerald, M, R. Penny, P. Swan, C. Swan, Space Elevator Architectures and Roadmaps, ISEC Study Report, lulu.com, 2015

6. Study, design and test potential approaches for the gripping mechanism for tether climbers to move along the tether's 100,000 km length.
7. Study robotic Apex Anchor functions with the anticipation that they will lead to a complex satellite. This should include the concern of operating and maintaining the Apex Anchor at a distance of 100,000 kms.
8. Understand and design approaches for power to the tether climber for the hazardous first 40 km inside the atmosphere.

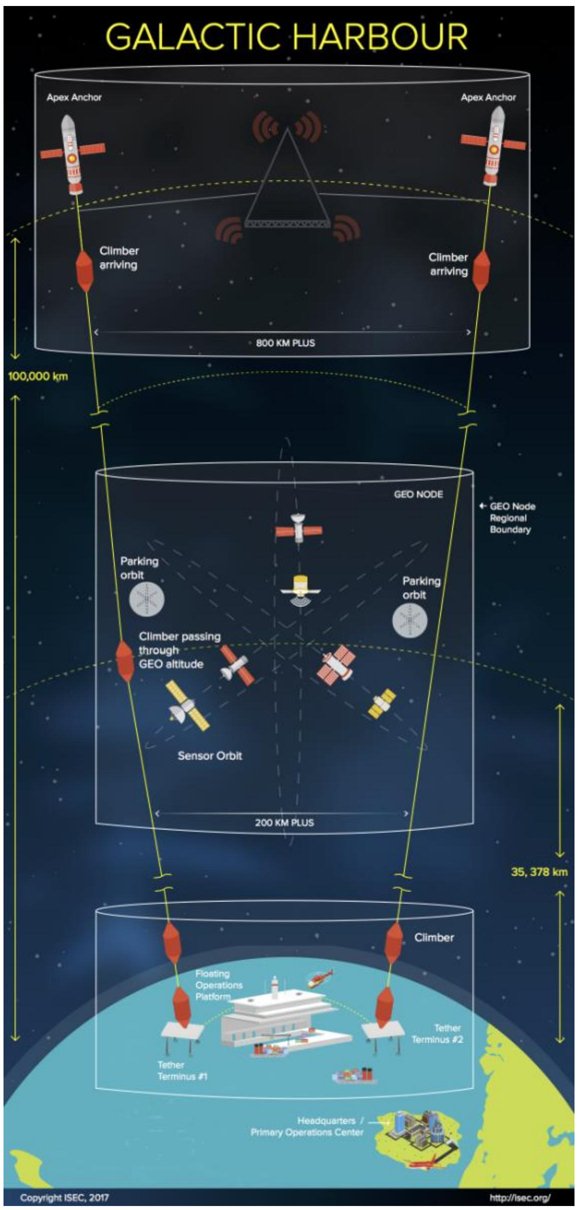


Figure 1 Galactic Harbour (2017)

1.3 Incorporating a Plan requires a Vision:

The Space Elevator vision is straightforward in that it has a future architecture and words that show its place in the development of space:

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.

2.0 The Galactic Harbour Transportation System Concept:

Two Space Elevators per Galactic Harbour have a capability of moving massive cargo on a green road to space.[3] The transportation strategy is to link the Space Elevator Transportation System to the Space Elevator Enterprises that will develop along the permanent infrastructure. This unifying vision is called the Galactic Harbour. It beats the Gravity Well in an environmentally friendly manner while creating commercial ventures along the infrastructure, such as facilities for refueling, repair and construction.

The future for humans to open up off-planet activities is immense when one realizes that the permanent space access infrastructure consists of an Earth Port with Floating Operations Center, a Tether Segment stretching from the surface of the ocean to the top of the tether, Tether Climbers to move massive cargo up and down the tether, and the Apex Anchor at the upper terminus. The major characteristics of this architecture relate to a permanent transportation infrastructure; such as:

- Revolutionarily inexpensive to GEO [$100/kg to GEO]
- Commercial development similar to bridge building
- Routine [daily launches]
- Safe [no chemical explosions from propulsion]
- Permanent infrastructure 24/7/365/50 yrs. [bridge similarities]
- Massive loads with daily launches per elevator [170,000 tonnes / yr]

[3] Eddy, J, Peter Swan, Cathy Swan, Paul Phister, David Dotson, Joshua Bernard-Cooper, Bert Molloy, "Space Elevators: The Green Road to Space," ISEC Study Report, lulu.com, 2021.

- No shake-rattle-roll during launch
- “Big Green Machine” has little impact on global environment
- No consumption of fossil fuel.
- Does not leave space debris in orbit

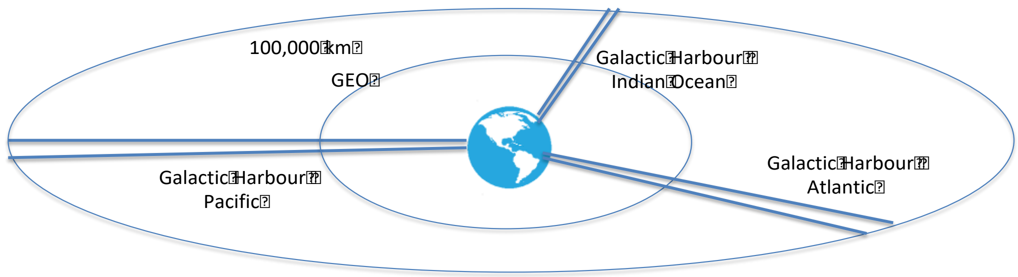


Figure 2: Vision of three Galactic Harbours

In addition, there are unique characteristics of Space Elevators with a rapidly moving Apex Anchor (7.76 km/sec) which enable remarkable opportunities for off-planet missions. This combination of three major strengths will ensure constant support to missions beyond Geosynchronous altitude. Strengths to Mars:

- Rapid Transit 61 days minimum
- Release daily 365 release opportunities each year
- Massive tonnes: 170,000 tonnes per year to GEO and Beyond

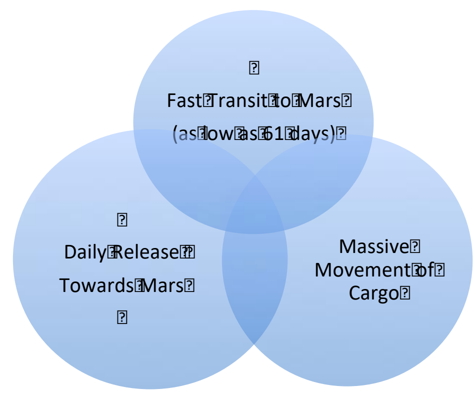
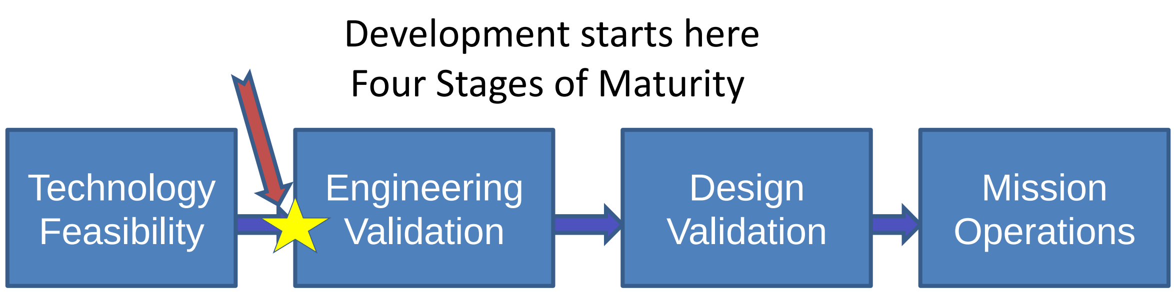


Figure 3: Strengths of Interplanetary Flights

3.0 Space Elevator Transportation System – Development Phases: Over the last ten years, the Space Elevator community has recognized that it has taken the concept through the feasibility stage of maturity and has shown that it can be built. The four stages are laid out in the figure below with the arrow pointing to our current location in development of this mega project. We have accomplished the technology investigation stage and moved into the “show me” stage where a taxonomy of tests demonstrations and simulations will be accomplished.

Figure 4, Four Stages



3.1 Leaving Technology Feasibility: As explained earlier, the Technical Readiness Assessment was accomplished at the preliminary level and illustrated in the two IAA reports. The movement into the second stage of maturity was successful and illustrated during the first IAA study (2013). Table 2 shows the conclusions from the study agreeing with the concept of moving into Engineering Validation Stage.

3.2 Entering Engineering Validation:

The next step has been initiated to move into the Engineering Validation phase. Galactic Harbour Associates has started that phase with activities that will lead to the full up development plan. The plan for this development includes a vision that reaches across the space arena by providing a set of permanent space access infrastructures around the globe. During the study of roadmaps, the team came to the conclusion that moving into the hardware deployment stage would need many of the sub-system and system level demonstrations that have been discussed. As such, the document laid out many capstone demonstrations that would pull together the challenges inside each major segment of the Space Elevator. This roadmap lays out a plan that can be achieved within the reasonable schedule discussed in both the IAA books and the ISEC studies. These roadmaps are consistent with the four stages of development for a mega project.

Table 2: Study Results

Space Elevator Segment	Conclusion from the IAA study
Earth Port	Ready for engineering validation program
HQ & Primary Ops Center	Ready to start an engineering validation program
Tether Climber	Engineering model assemblies needed – then start validation program
Geosynchronous Node	Engineering discussions and demonstrations with key members of industry are needed to establish collaboration
Apex Anchor	Engineering discussions and various simulations are needed – then collaboration with engineering organizations and academia should begin.
Tether Material	Prime material candidate has been identified; laboratory segments have been developed and tested; and, production demonstrations must be initiated.
Collision Avoidance	Architectural engineering definition is being finalized. Candidate concepts are identified. On orbit performance demonstrations are needed.

The first intermediate destination of the roadmap was the completion of the Preliminary Technology Readiness Assessment (move out of Stage One) while the second destination would be the aggressive initiation of the testing and demonstrations to support the engineering validation stage. Many of the questions to be addressed in this stage of maturity are:

1. Can it be built?
2. Examine Industry's program roadmaps to support segment development
3. Assess the schedule and technical risks
4. Delineate on-ramp criteria for various "late incorporations" to the baseline
5. Set criteria and standards for the design validation
6. Finalize the baseline technical performance and how that drives design

3.3 Entering Phase Three and Four

These stages of development are the portion where industry delivers their segments to the prime contractor based upon the baseline design and systems requirements documents. There will be massive testing and system level demonstrations prior to the completion of the four phases of maturity. A short summary would be:

- Phase Three: Validate Design Approaches
  - Service the Risk Buy down
  - Measure Design versus Performance Baseline
  - 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

4.0 The Galactic Harbour Transportation System Concept:

The transportation strategy is to link the Space Elevator Transportation System to the Space Elevator Enterprises that will develop along the permanent infrastructure. This unifying vision is called the Galactic Harbour and will enable massive movement of cargo while being environmentally friendly.

4.1 Space Elevator Transportation System – Massive Movement of Cargo

As shown in the 2020 ISEC study report[4], Space Elevators' delivery statistics to destinations (roughly 70% - with other 30% reused) are remarkable. Movement of mass by the mature Space Elevator Community dwarfs the past and future performance of rockets. Can you image 170,000 tonnes per year to GEO in a green manner saving our environment as well as fulfilling the needs of our various programs?

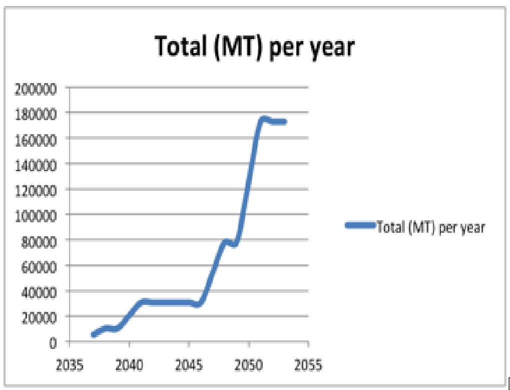


Figure 5: Tonnes per Year

4.2 Space Elevator Strategy: Dual Space Access Infrastructure

The strategy of the Space Elevator Community is that the strengths of rocket launches (along with their difficulties) should be combined with the strengths of the Space Elevator to enable the dreams of so many to go to space. We recognize there are three principal strengths of advanced rockets: 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. The strengths of a permanent infrastructure with daily, routine, environmentally friendly and inexpensive attributes come with Space Elevators. These strengths will be compared to the difficulties of executing a Space Elevator developmental program. Space Elevators will not be ready for initial human migration off-planet. However, once colonies are established on the Moon and Mars using rockets, Space Elevators will enable robust growth by moving massive cargo, daily, inexpensively, environmentally friendly, and routinely.

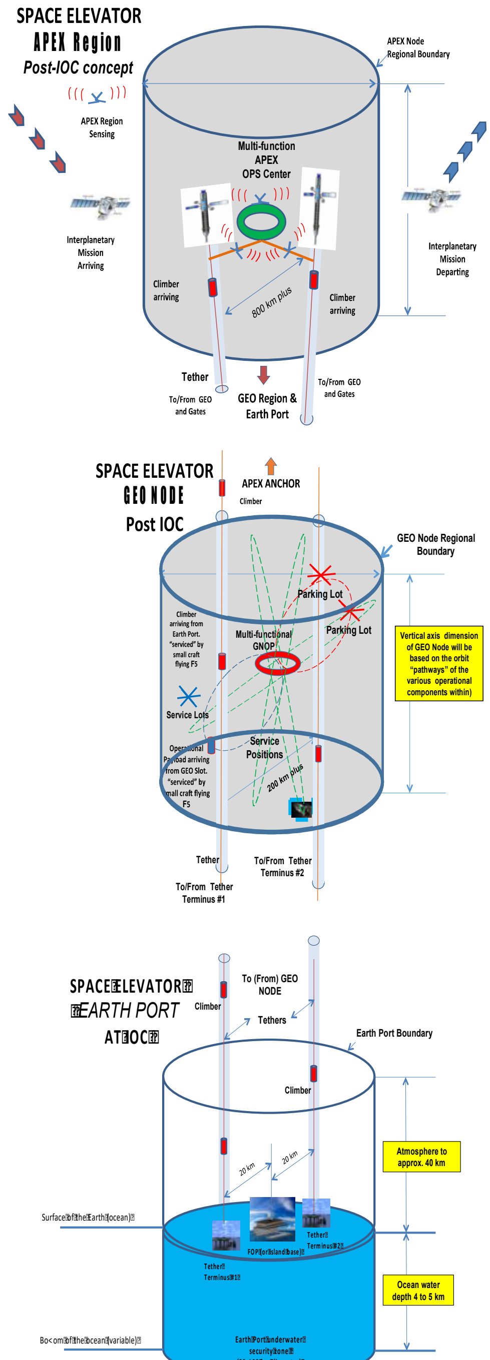


Figure 6: Galactic Harbour's Three Regions

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4 Swan, P., M. Fitzgerald, "Space Elevators are the Transportation Story of the 21st Century," ISEC Study Report, www.lulu.com, 2020.

5.0 *Where are we, now?*

The Space Elevator has started Engineering Validation because:

- The ISEC team has been assessing the technology feasibility situation since 2008
- Recently the team has begun an open dialog with members of industry, academia, and others who could be the deliverers of segment solutions
- Industry will show how the needed technologies are being matured and when they could be dependably available
- These preliminary readiness assessments were completed in Stage One as the exit criteria.

The Space Elevator and Galactic Harbour Concepts are ready for Prime Time

6.0 ***Conclusion:*** The conclusion from the analysis going into this paper is that there is a solid case to proceed ahead with the Space Elevator development.

The Space Elevator will be the Transportation Story of the 21st Century

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(note: all ISEC reports are on www.isec.org in pdf for free)