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Space Elevator GEO Node and Apex Anchor Architectures

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Abstract

One of the principle elements of the International Space Elevator Consortium's (ISEC) action plan towards an operational space elevator is to conduct year-long studies addressing critical topics. This year, ISEC has chosen to address the design considerations for the Geosynchronous Earth Orbit (GEO) Node and Apex Anchor. As was discussed in the Space Elevator Architectures and Roadmap study report, ISEC understands where the technologies are today and where we would like them to be to reach Initial Operational Capability (IOC), and beyond. The goal of this study team was to add to the "body of knowledge" relative to the two topics addressed herein. This will help us stay focused on our destination as stated below. Our Destination is IOC for a system comprised of two space elevators, with separate Marine Nodes and Apex Anchors each with 100,000 km usable tethers, and a single Headquarters and Primary Operations Center. This paper will discuss the study and show the results from this year long activity.

1. Introduction*: The Apex Anchor and GEO Node are major segments in a complex space elevator transportation infrastructure and should be understood as significant entities, in their own right, as well as integrated segments. As the system matures, a clear distinction between the transportation revolution and the visionary entrepreneurial enterprises will emerge. The concepts of the Space Elevator Transportation System and Space Elevator Enterprise must be distinguished; and clearly so! A Space Elevator Transportation System is the revolutionary core of our vision and the Space Elevator Enterprise encompasses the transportation core and entrepreneurial manifestation of what it will become. A strategic approach has emerged; [1]

The Strategic Approach

> The Strategic Approach is the International Space Elevator Consortium's guiding theme for the technical development of a Space Elevator. ISEC has spent some time discussing how to turn a long-term vision into a long-term plan. The problem is that a plan usually implies either a specific schedule, a specific budget, or both. We have settled on the notion of "an approach" while disdaining budget and schedule specifics.

* This paper reflects results from one year study by ISEC on the topic. Much of the content is paraphrased from the study activities. [1]

The "strategy" is to link the Space Elevator Transportation System to the Space Elevator Enterprise within a Unifying Vision: the Galactic Harbour. The Space Elevator Transportation System will be the core priority construction activity; and, its success will be the foundation of the Space Elevator Enterprise. They will be built in a manner separate from each other but not in isolation. This "separate but not segregated" paradigm establishes both the prioritization and collaboration between and within our near parallel efforts.

***2.* Process:** The International Space Elevator Consortium (ISEC) has developed a process for selectinga key topic for its yearly focus. This includes conducting an in-depth analysis, year-long study, to assess various aspects of the topic. This focus enables the ISEC to prioritize activities and leverage volunteers with expertise in the chosen fields. The single focus on a topic for a particular year enables the community to bring its strengths together and address the topic at the yearly conference, inside the organization's journal (CLIMB), magazine (Via Ad Astra) and through the study process with a resulting report.

3. Definitions: To ensure complete understanding during this year's study report, the following definitions are provided: [1]

Space Elevator Column: The volume swept out by the tethers during normal operations starting at the Earth Port [a circular area within which it operates] and extending through the GEO Region up through the Apex Region. These columns of space will be monitored, restricted, and coordinated for all who wish to transverse the volume. The current concept is similar to the FAA's Automatic Dependent Surveillance – Broadcast approach. Satellites, aircraft and ships will announce where they are and coordinate motion through the space elevator column. Each space elevator has a column of allocated volume.

Earth Port Region: The volumetric region around each Earth Port to include a space elevator column for each tether and the space between multiple tethers when they operate together. The Earth Port Region will include the vertical volume through the atmosphere up to where the space elevator tether climbers start operations in the vacuum and down to the ocean floor.

Earth Port: A complex located at the Earth terminus of the tether to support its functions. These mission elements are spread out within the Earth Port Region. When there are two or more termini of tethers, the Earth Port reaches across the region and is considered one Earth Port. [2, 3]

GEO Region: This Region encompasses all volume swept out by the tether around its Geosynchronous altitude, as well as the orbits of various support and service spacecraft "assigned" to the GEO Region. When two or more space elevators are operating together, the region includes each and the volume between elevators.

GEO Node: A complex of Space Elevator activities positioned in the Space Elevator GEO Region, directly above the Earth Port. There will be several sub nodes; one for each tether, one for a central main operating platform, one for each "parking lot," and others.

Apex Anchor Region: The region around the Apex Anchor is defined by the amount of motion expected at the full extension of the tether. The region is the volume swept out by the end of the tether during normal operations. When two or more space elevators are operating together, the region spreads to the volume between.

Apex Anchor: A complex of activity is located at the end of a Space Elevator providing counterweight stability for the space elevator as a large end mass. Attached at the end of the tether will be a complex of Apex Anchor elements such as: reel-in/reel-out capability, thrusters to maintain stability, command and control elements, etc. [Note: nothing stays at that altitude unless attached to a tether].

The Space Elevator will be a transformational transportation system. Two more concepts are presented to ensure understanding: 1) our destinations, and 2) developmental sequences. The sequence of development will proceed until the space elevator can robotically move payloads (called Initial Operational Capability – IOC) towards a more robust system performance called Full Operational Capability (FOC).

Our Destinations

- **The Initial Operational Capability (IOC)** consists of a system comprised of two space elevators with one Earth Port and two terrestrial terminus, two Apex Anchors each with 100,000 km tethers, multiple tether climbers and a single Headquarters and Primary Operations Center. This system will be capable of moving significant payload tonnage [20 Metric ton] to GEO and beyond several times a week from each space elevator.

- **The Full Operational Capability (FOC)** contains two tethers per elevator system (100,000 km strong tether), each with a tether terminus platform inside the Earth Port, GEO Node, Apex Anchor, and with a single Headquarters and Primary Operations Center. This system will be capable of moving an estimated 70 Metric tons to GEO and beyond several times a week (with passengers).

The following terms are an assembled set of steps for understanding the development of this unique space transportation system. Certain terms have been suggested to express the steps that will be needed to accomplish a full up capability. Each step has an extended phase of tests, simulations and demonstrations. The following are the space elevator developmental phases with explanations following [Ref 1]:

- Pathfinder
- Seed Tether
- Single String Testing
- Operational Testing
- Limited Operational Capability (LOC)
- Initial Operational Capability (IOC)
- Capability On Ramps leading to Full Operational Capability (FOC)
- Full Operational Capability

Pathfinder: This pathfinder is designed as an in-orbit flight demonstration of all sub-systems and elements of a space elevator. One essential point is to achieve this early pathfinder in-orbit experiment using near-term technologies – i.e. the tether material need NOT be a full-up CNT ribbon (maybe composed of current Kevlar or beta material of some type).

Seed Ribbon Deployment: This component of the Space Elevator will be the basis for a feasible first step in building a space elevator – deployment. The estimate of the technological readiness (in about 2031) will project for a much less capable ribbon being deployed and captured by a "start-up" Earth Port.

Single String Testing: In early forms, single string testing could "simply" be an end-to-end simulation of a segment or even the entire architecture. Single string testing is largely investigative, aiding engineering progress and maturation.

Operational Testing: OT is that set of test events intended to validate that a system or segment performs as designed in an operational context.

Limited Operational Capability: The idea of LOC is similar to the baseball concept of spring training. All aspects of the Architecture are included and the hardware has been operationally deployed. This phase is good for assessing whether the operating personnel are knowledgeable and trained, that payload customers are aware & understand how this Space Elevator works for them, and operational instruction documents (ie., checklists) are finalized and vetted. This limited capability will be concurrent with tether buildup activities – adding tether mass from tether buildup climbers.

Initial Operational Capability: System engineering competency is part of what IOC is. These "engineering competencies" – validated by execution of the sequenced events – are the functional requirements of the Space Elevator at IOC. The Space Elevator will function as designed and tested with safety & certainty, and in communications contact with HQ/POC.

On-Ramp to FOC: The need for Space Elevator capability growth after IOC should be obvious; but to be clear, the Space Elevator post-IOC on ramp activity will be a formal process by which we add more of the IOC's functionalities, improved versions of the IOC functionalities, and new Space Elevator functionalities. The result will be movement towards Full Operational Capability (FOC) with incremental additions of capability. In practice, on ramp activity is ➔ More; ➔ Better; and then ➔ New.

Full Operational Capability: The visionary aspect of the Architecture includes tourism, interplanetary travel staging, hospitals, factories, power generation and a multitude of operational support services. The FOC vision for the Space Elevator will expand with time and be achieved by expansion via the "more", "better", and "new" paradigm cited in the on ramp sequence. The basis of each expansion will be the engineering maturation achieved by progressing through the sequenced steps cited in this paper.

4. Apex Anchor

This section addresses an Apex Anchor Node of a Space Elevator Transportation System. The 2012 ISEC Study Report, "Space Elevator Concept of Operations," [4] describes missions of the Apex Anchor as follows:

> "The Apex Anchor mission is multi-dimensional; but, its principal function is to provide stability for the space elevator as a large end mass. This will ensure a firm tether for the climber, and provide a constant outward force. In addition, the Apex Anchor will have the mission of reeling the tether in and out as required for various tasks such as debris avoidance, damping tether end librations, and reacting to emergencies."

This section describes an Apex Anchor and how to develop it into an end mass at an estimated altitude of 100,000 km. A quick look at the Apex Region will set the stage for further discussions. This section will then describe apex anchors, discuss general approaches for building or creating them, and illustrate a four-Stage approach for development. The baseline concept develops the Apex Anchor from the original deployment satellite as it moves to the top at 100,000 km while extending all of its tether. The mass is then increased to ensure balance with the rest of the tether mass build-up below it. The last portion will show the Apex Anchor functions necessary to reach IOC and beyond.

The Apex Region will result from an understanding of the volume swept out by the upper tether terminus. There are a few items that are assumed when discussing a future Apex Region:

- The full volume of this Apex Region is in "hard" vacuum.
- The volume rarely has transits of space rocks or human spacecraft.
- Freedom to operate within the Apex Region will become extremely valuable.
- Estimates of this swept out volume are currently being looked into with the 2017 ISEC Study entitled "Design Considerations for Space Elevator Modelling and Simulation." [5]

- Significant fuel would be required for thrust to keep objects within the region when they are not attached to the Apex Anchor.

A quick vision of the Apex Anchor was given in the IAA study report [6] to help explain the concept of the Apex Anchor as a key segment of a space elevator infrastructure. This vision establishes the total concept well past IOC toward FOC.

> "An Apex Anchor is the upper terminus (counterweight) of the Space Elevator. Apex Anchors will have solar arrays for power and serve as an end platform for climbers and a station for climbers that are preparing to descend. Several other activities will occur at the Apex Anchor to include its use as a platform to construct, deploy, recover, maintain, and repair satellites. It will also be a lab to conduct experiments utilizing the low-"g" environment and to analyse the material mined and retrieved from the Moon, asteroids, or other planets. At a later stage, it might be a facility for tourists. The Apex Anchor will also be equipped with facilities to manage tether dynamics, telecommunication, attitude control, collision avoidance of meteorites or space debris, manned activity including EVA, and transfer vehicles. The Apex Anchor will enable construction of space systems and refueling of spacecraft. Operations of the Apex Anchor are controlled at the HQ/POC. Operations will have multiple activities during construction with continuous activity once commercial operations commence. There would be several space elevator center of mass management activities including: reeling in or out of the tether from the Apex Anchor, thruster control of motion at this upper terminus, and coordination with HQ/POC ensuring a stable upper tether. In addition, the motion for avoidance of space debris could also be controlled or initiated from the Apex Anchor." [6]

Deployment begins with the deployment satellite being raised to GEO. The Apex Anchor has been discussed at a very cursory level during studies of three major modern space elevator architectures. The discussion below will try to explain the four stages for stabilizing a space elevator with an outward force at its Apex Anchor. [6]

Stage 1 – Initial Deployment:
Currently, the only way to get to a GEO orbit for the release of the tether is through rockets with limitations on mass and difficulties in cost and schedule. The first step is to assemble the Tether Deployment Satellite in Low Earth Orbit. This would include multiple launches and assembly on orbit – both capabilities will be improving as launch opportunities approach [+/- 15 years].

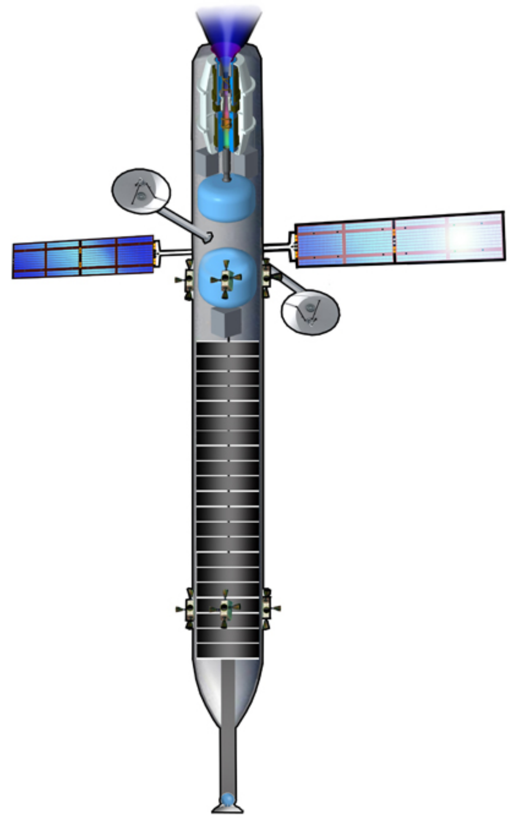


Figure 1 Deployment Satellite Concept [image by P. Ellis]

After assembly in orbit, the large mass [>80 MT] would be raised to a GEO altitude orbital slot with efficient engines that may take up to six months to reach GEO. A concept of this deployment satellite is shown in Figure 1.

There is an inherent need for an Apex Anchor for stability. Once the massive satellite reaches its GEO altitude, it will release the seed tether – downward only. This image shows 21 reels, in sequence, providing the 100,000 km of initial (seed) tether. There is a requirement to increase angular momentum with rocket thrusts during this deployment activity. This could require refuelling at GEO to continue the smooth deployment of the tether. Once the preliminary Apex Anchor has been established with a single string tether to the Earth Port, both the Apex Anchor mass and the strength of the tether must be reinforced.

Stage 2 – Apex Anchor Build-up to Match Tether Mass Build-up: Once the initial portion of the tether has been deployed downward towards its Earth Port terminus, tether stability control is shared between the Apex Anchor and the Earth Port. During the build-up of tether strength and mass toward the Initial Operational Capability, the mass needed at the Apex Anchor must increase consistent with the tether build-up. The approach to add tether mass and Apex Anchor mass in parallel is being discussed with unique ideas and activities required to accomplish construction of a space elevator. Once the stability of the tether is achieved and a sufficient mass/strength of the tether and the Apex Anchor are reached, the development of a second space elevator must be initiated to ensure our continued ability to "beat gravity." This would probably require a second assembly at LEO, movement to GEO and deployment. At the end of the deployment phase, the deployment spacecraft becomes a principle part of the Apex Anchor. This would include computational capability, thruster ability, fuel storage [with refuelling capability], and communications links to the HQ/POC, Earth Port, tether climbers, and customers' satellites.

Stage 3 – Initial Operations Capability: The Apex Anchor at IOC will have as its primary mission the stability of the entire tether. This will require the correct mass, thrusters to move the Apex Anchor as needed, reel-in and reel-out capability, as well as the off-load and on-load capabilities retained from the build-up phase.

Stage 4 – Customer Support toward FOC: This phase will be consistent with the growth of the space elevator. Customers will determine where they want their assets delivered and what (if anything) they want to accomplish at the Apex Anchor. This could stretch across the full spectrum of space operations of the future, to include at least refuelling, servicing, repair, construction, human habitats and inbound capture as well as routine release into the solar system.

Once the Apex Anchor reaches its end altitude, build-up of the tether and apex Anchor begins. Once they reach the capability of IOC, the functions to be achieved are estimated to be: [1]

- **Deployment Body Support:** Provide support to full infrastructure during initial deployment of tether. As the total space elevator is derived from the process of deploying tether and Apex Anchor, this segment's function will dominate during deployment and early build-up phases.
- **Stability Support:** Continuous control and stability of the Apex Anchor must be maintained. Concepts for control of the dynamics of the tether are expanding as more people look at the problem. Some elements of tether dynamics control are:
  - **Mass** at the upper end provides inherent stability,
  - **Reel-in and reel-out** will provide forces to the tether that can be used to dampen motion
  - **Thrusting** in horizontal directions can dampen motion in the total tether.
  - **Tether climbers** residing at the Apex Anchor, or along the tether, could be leveraged to climb down the tether – thereby putting forces on the tether in a controlled manner to damp out motion.
- **Build-up Support:** The obvious activity is the build-up and strengthening of the tether with additional mass supporting appropriate tether strength requirements. Support from the Apex Anchor will be in the communications, control and acquisition of any of the tether build-up climbers reaching the Apex Anchor. In addition, there will be the task of off-loading and ensuring safety when mass is delivered to the Apex Anchor, whether it be build-up climbers or derelict satellites.
- **Sever Support:** Reaction to the severing of a tether must initiate multiple pre-planned activities. The concept being developed relies upon the belief that the space elevator can survive a sever if it is cut in the lower reaches of space. If the tether is cut at the highest danger zone, 800 km altitude, the remainder of the space elevator will react to the loss of mass and connection force. The belief is that with quick reaction at the GEO Node and the Apex Anchor, the total space elevator above that sever altitude might be saved. This would require many actions in a timely manner such as release of tether from both GEO Node and Apex Anchor as well as motion of tether climbers on the remaining tether. Knowledge of the cut must be almost instantaneous [can be accomplished with today's sensors and communications capabilities], while the support must be pre-planned and almost instantaneous.

Once the system becomes robust and approaches FOC, these additional functions will be needed:

- **Infrastructure Support**: Provide stability, acceleration, power, communications, environmental conditions, security and energy. Tether repair capabilities will enable continuous monitoring and immediate response to concerns. The growing belief within the Space Elevator community is that anything above GEO will be coordinated at least and probably controlled from the Apex Anchor.

- **Customer Support:** Provide stability, accelerations, power, communications, environmental conditions, security and energy. It would seem natural, that when customers arrive at the Apex Anchor, they will expect normal support for their equipment, payloads, satellites, and support personnel. This would definitely include hotel-like accommodations as well as spaceport-like support operations.

- **Docking Support:** Provide capability to off-load and on-load systems from tether climbers and/or external satellites. This would include rendezvous with spacecraft coming from CIS-Lunar space as well as along the space elevator. As customers approach the Apex Anchor, their expectations will include a haven for their equipment and themselves as well as the simple activities of safely docking and undocking.

- **Refuelling Support:** Enable refuelling of space systems as well as the Apex Anchor itself. This capability could be a commercial mission as well as an aspect of Apex Anchor capabilities. One of the questions on the table now is where does the fuel come from? It would seem that bringing the fuel up from Earth would be expensive [cheaper than launching of course]. Perhaps the Apex Anchor is a location for acquiring fuel from Lunar or asteroid sources and selling it for a profit at the upper terminus of the space elevator.

- **Human Habitat:** Support to humans will be necessary at the Apex Anchor. This will ensure that humans will be safe, comfortable, and entertained. The concept of a spaceport at the Apex Anchor has many advantages. Not only would it be a safe haven for humans [easy up and down], but it would be the focus for passengers going both ways. A human habitat would enable many functions at that altitude to include construction crews for interplanetary craft, operations personnel for commercial activities at the spaceport, and holiday activities with spectacular views. The advantage of having a small acceleration force inherent in the location could be a tremendous lever for construction or repair of spacecraft occurring in a hanger like spaceport.

The following image shows the Apex Anchor Region in a form that is understandable – a region where two tethers terminate and the Apex Anchors support the needs of space elevator customers (both transportation and enterprise), Figure 1.

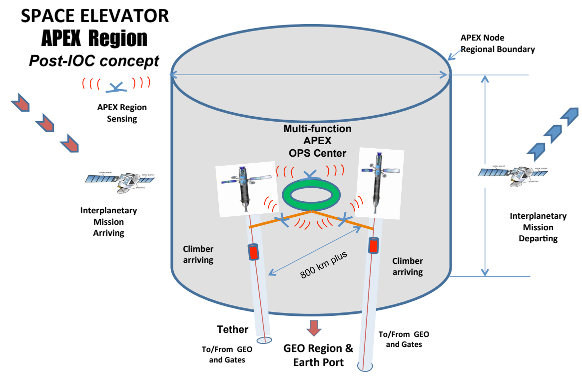


Figure 2, Apex Anchor, Post IOC

5. GEO Node

Early on in our considerations of the design of a GEO Node [pre-IOC], the International Space Elevator Consortium knew that the GEO Node offered no active primary function to the Space Elevator's role re: transportation access to space. Simply stated, the Space Elevator's climber could pass through GEO on its trek to the APEX Anchor. In that sense, GEO is a place, not a destination. The GEO location is valuable "only" because that is where initial customers will release their satellites. Thus, the GEO Node functional makeup was originally conceived as minimal; two tether columns passing through and a GEO Node Operating Platform (GNOP) for overhead functions (shown in a slightly inclined orbit). See Figure 5.

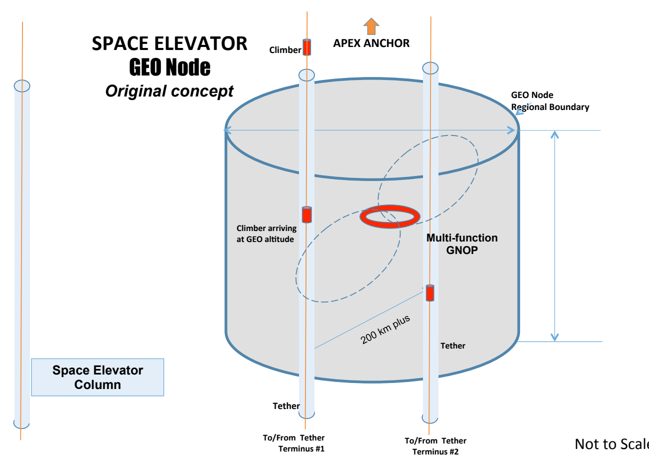


Figure 3 This Operational View was the original GEO Node

The only action within the GEO Region, pre-IOC, was to be the release and/ or capture of payloads to and from Climbers. However; with time, it became clear that ISEC needs some "active primary functions" at GEO well before IOC. Active primary functions are needed to test, monitor, and service the entire deployment process. We call them overhead functions.

The Pre-IOC deployment and testing process will take years. Deployment support functions should be preserved at the GEO Node for post IOC activities. The original thought process had assigned release, return and check out functions to Climbers. It is now clear that some of these functions could be accomplished by small, specialized spacecraft at GEO. A Climber / Tether / GEO / APEX functions trade has not been conducted. As IOC approaches, the GEO Region will be full of activity from individual tether climbers. They will be going through the region, off-loading and on-loading material needed to attain operational status. In addition, there will be situational awareness systems to monitor the “care and feeding” of both tethers and climbers within the region. This will lead to operational concepts managed at the HQ/POC. Figure 4 shows the Space Elevator Transportation System GEO Node at IOC with a minimum set of responsibilities, yet with great potential for future activities.

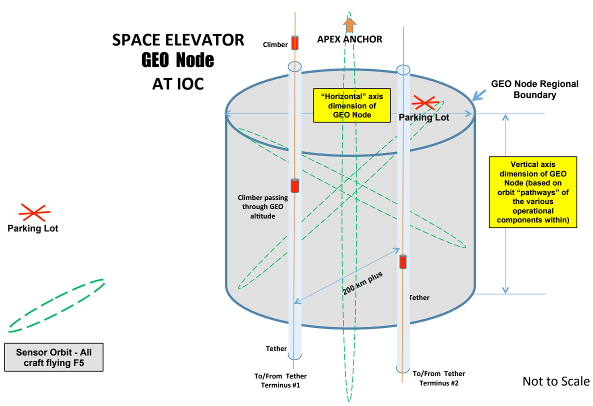


Figure 4 GEO Node at IOC

The activities of the GEO Node will be taking up room – a lot of room. ISEC expects a GEO Region of over 19 million cubic kilometers! This is based upon a GEO Region estimated to be 200 kilometers tall and 350 kilometers in diameter. The need for “room at the inn” at GEO starts early; and, some activities will persist for years. Approaching IOC, operational testing and training support needs will involve much of the GEO Region. A variety of assets will be parked at GEO supporting on-orbit deployment testing of all sorts. Test assets will be deployed to GEO as early as Sequence #3 (Single String Testing) when the latter phases of single string tests are to be conducted. Those support assets will be parked in the GEO Region when Sequences phases are completed. They will be awaiting post IOC modular growth / on-ramp activity.

GEO Node functions before IOC are to test, monitor, and service the entire deployment process. The pre-IOC deployment and testing process will take years. These same deployment support functions will be preserved at the GEO Node for the post IOC On-ramp activities.

Once the transportation becomes robust enough for IOC, the growth of both the transportation system and the enterprise system will be remarkable. The following are likely functions at the GEO Node

- Communications: The GEO Node communications functions will largely relate to the transactional communications within the region to support modular operations and the timely reporting of situational awareness concerns and operational surety. The GEO Region Operations Control Center will need distinct / unique embedded auto-communications functions to support collision avoidance, debris detection, intrusion, environmental event detection and full situational awareness.

- Maintenance: The modular design standard will emphasize Line Replaceable Units enabled by robotic replacement schemes. New or improved LRU modules must be certified as acceptable by appropriate engineering processes.

- Power Generation: All sorts of power needs to be generated to execute GEO Node functions and services. It may be that a mix of solar and space nuclear energy is needed. Energy Multiplier Modules’ (EM^2) nuclear elements are developing apace with Space Elevator needs.

- Propulsion: All objects within the GEO Node must actively maintain orbital position, avoid collisions, and manipulate orbital position to execute or receive function / service. A variety of propulsion types are expected to be used and maintained

- Payload Processing: Provide services as per customers’ request

- Payload Anomaly Diagnosis: A special case of payload processing provided as per customer request

- Local Operations Controls (Center): A sub element of HQ/POC with some local autonomy for collision avoidance, debris detection, space object intrusion, environmental event detection and GEO Region situational awareness.

- The GEO Node will have some responsibility for controlling tether dynamics (i. e. Reel-In / Reel-Out) in collaboration with the Earth Port, APEX Anchor and HQ Operations

- Refueling: Refuel GEO Node assets and payloads as part of servicing. Safety, surety, and environmental restrictions will be considered.

- Payload Transfer: A series of handling functions that enable payload/cargo movement from and to interim and final destinations.

- Security & Surveillance: The GEO Node will provide a range of surveillance sensing to support clients and GEO Node operations.

- Safety: The GEO Node will be a safe operational environment

6. Conclusions and Recommendations:

This study continued the push to improve the body of knowledge for Space Elevators. The authors concluded:

- The deployment and continued stability of the tether are the primary function of the Apex Anchor until IOC. This translates to:
  - a reel in/reel out (or climb up/climb down) capability,
  - a capability to fire thrusters (magnitude and direction) as directed by HQ/POC, and
  - support to customers who leverage the strength of the end-point of this space transportation infrastructure.

- The basic mass build-up for the Apex Anchor will initially be from spent climbers and derelict GEO satellites.

- The GEO Node is expected to become the center piece of a Space Port that provides "overhead" services such as repair/assembly, refuelling climbers, loading and off-loading supplies, servicing tugs and many other functions to a myriad of customers, after IOC.

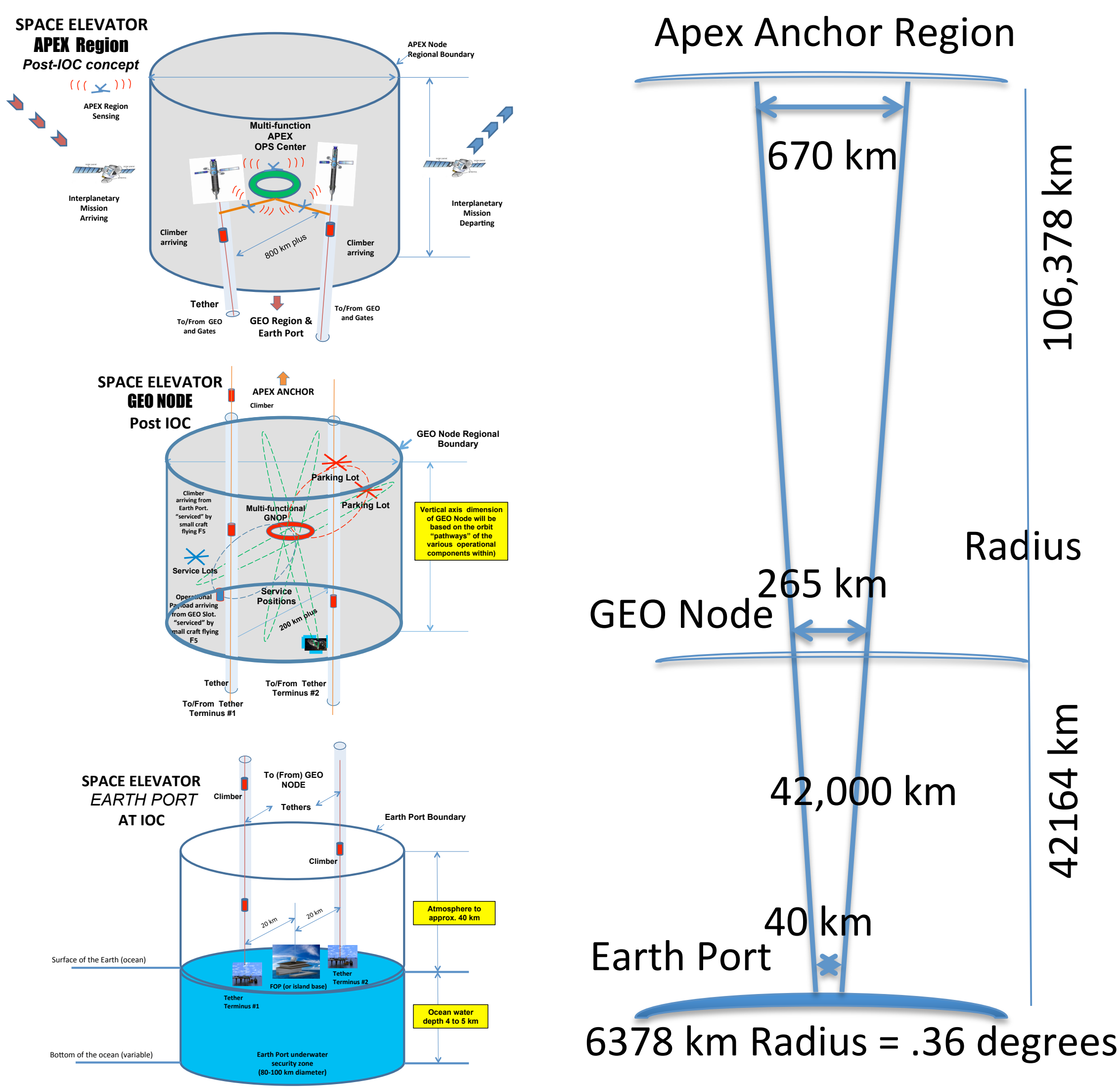
- Today's technology should suffice to understand the needs of Apex Anchors, GEO Nodes, and their customers. However, future technological capabilities will indeed enhance capabilities in space, especially at these complexes.

- While one is evaluating and developing the Apex Anchor and GEO Node concepts, one must be cognizant of Earth Port design characteristics. Indeed, there are several parallels within this tremendous space elevator transportation infrastructure between the Earth Port and both the GEO Node and Apex Anchor. One of ISEC's favorite images illustrates this and is shown below.

7. Vision

This vision is a series of individual images stacked along side a visualization of the space elevator regions leading to the Galactic Harbour. The definition and layout of the Galactic Harbour Vision is given in a parallel paper at the conference [7]. "How the Space Elevator Grew into a Galactic Harbour"

Figure 17, Space Elevator Regions



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