How should the Smart Apex Anchor be developed?

International Space Elevator Consortium

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ABSTRACT

This paper proposes a solution to the problems of engineering a Smart Apex Anchor for an Earth based Space Elevator.

Following the launch of the initial Smart Apex Anchor and the Tether deployment, the proposed *Tug Collection Programme* captures derelict satellites to form additional mass for the Smart Apex Anchor. The derelict satellites are collected from the disposal orbits and are used to maintain the mass ratio between the Tether and Smart Apex Anchor.

The requirements for a Smart Apex Anchor are reviewed and evaluated against the proposed solution. Methods to capture and engineer these satellites are compared, and a low risk non-impact method is proposed.

1.0 INTRODUCTION

The Space Elevator concept proposed by the International Space Elevator Consortium allows large masses to launch into space in a more efficient, economical, environmentally friendly manner compared with rockets and other space launch vehicles.

Earth based Space Elevators are composed of 100,000km[1] of Tether, a Climber, an Earth Port, Interplanetary Payload and a Smart Apex Anchor. The Tether is constructed using either Graphene, Carbon Nanotubes or Boron-Nitride Nanotubes[2]. The Tether is anchored to the ground at the Earth Port, which is located along the equator and at the corresponding Smart Apex Anchor above Geostationary orbit (GEO). The gravitational acceleration due to the Earth and the centripetal force acting on the Smart Apex Anchor allow the Tether to remain taught during its operation.

The Climbers have a mass of 6 tonnes and the capability to carry a 14-tonne payload. The mass of the Climber will remain constant from leaving the Earth Port on the surface of the ocean to reaching geostationary orbit. This exceeds the rocket equation, as only 4% of the initial mass reaches the same orbit, this is because rockets use chemical propellants whereas the Climbers ascend the Tether using an external source.

When launching satellites into GEO orbits, rockets leave behind upper stages[3] in lower orbits as space debris. As the number of rocket launches increases, the risk of collision with subsequent space debris increases.

When the satellites are no longer in operation at GEO, the derelict satellites are left in orbit or are propelled into the Disposal orbit (200km above GEO). Whereas the Space Elevator doesn't release any debris into orbit. Space debris causes several issues and poses risks to both rocket missions and the ability of sustaining the satellites in orbit. Space debris also poses a risk to the Space Elevator.

The Space Elevator by comparison is environmentally friendly and sustainable in the long term. It is electrically powered and does not leave space debris in its wake.

This paper introduces the derelict satellite *Collection System*. A *Tug spacecraft* is used to collect and transport the derelict satellites to the Smart Apex Anchor. The requirements and other possible materials are investigated to find the optimal solution. It focuses on the initial concepts and proposes an environmentally friendly, efficient solution to manufacturing the Smart Apex Anchor.

2.0 SMART APEX ANCHOR OPERATIONAL REQUIREMENTS

The overarching function of the Smart Apex Anchor is to act as a multi-dimensional counterweight to provide stability[4] for the space elevator by keeping tension in the Tether.

To do this, the Smart Apex Anchor will have sufficient mass to maintain a constant centripetal force to counteract the Earth's gravitational acceleration.

2.1 Operational Requirements

For initial operations capability, the Tether needs to reach a length of 100,000 km and a mass of 6300 tonnes[5]. The Smart Apex Anchor will have an initial mass of 14 tonnes and will grow to the required 1900 tonnes. The initial mass of the Tether will be 40 tonnes, as the mass of the Smart Apex Anchor is 30% of the Tether.

Following the deployment of the Tether, the Smart Apex Anchor will have a reel in and reel out system, to avoid collisions with space debris and other objects. It will also dampen the vibrations acting along the Tether during operation.

As the Tether infrastructure is further reinforced[6] its mass will increase. Therefore, the Smart Apex Anchor will need to compensate through a combination of moving to higher altitudes and gaining additional mass to maintain the appropriate ratio of counterweight to Tether weight.

The Smart Apex Anchor will communicate with the Earth Port and the Climbers, and its position will be controlled using 3D axis stabiliser engines and will be tracked using GPS. It has many similar attributes to satellites.

The term Smart Apex Anchor used to describe a station capable of moving to meet the changing environment of the Tether and Climber masses, the Tether Vibration, Tension, and collision avoidance, and was illustrated by the ISEC Board including Pete Swan PhD.

2.2 Industrial Application Requirements

The four main industries that will utilise the space elevator are:

- Science
- Space Exploration
- Satellites
- Tourism

2.21 Science

The Smart Apex Anchor can be used as a platform to test materials and perform experiments in microgravity[4]. A laboratory equipped with resources to analyse samples mined from the moon, asteroids, and other surfaces is required for the Science industry. The Smart Apex Anchor will require an energy source to power the lab; solar arrays built into the Smart Apex Anchor will be the best option, as it's a clean renewable energy source.

2.22 Space Exploration

The Smart Apex Anchor may also be used to construct larger scale inter-planetary and interstellar ships. Design concepts have been studied, such as Project Scorpion[7] for inter-planetary and lunar landing missions, or Project Icarus[8] for interstellar missions, but are not feasible to build on Earth due to their size.

2.23 Satellites

The Smart Apex Anchor can also be used as a platform for satellites, Climbers and other manmade objects orbiting the Earth. The platform will be designed to carry out construction[9], deployment, recovery and repairing of satellites, Climbers and any other objects. Therefore, the Smart Apex Anchor will need to have docking capabilities for these objects.

Management of Tether dynamics and telecommunications will be essential as well as attitude control when operational. These requirements were discussed in the IAA paper ''Road to Space Elevator Era[3]" alongside the equipment for manned activity including EVA and transferring vehicles.

2.24 Tourism

Space Tourism is a growing industry and until recently is very expensive as rockets have been the only option until the design of the Space Elevator. To run a Space Hotel, the Smart Apex Anchor will need to have oxygen, water, food, a protective shielding from radiation and a feeling of Earthlike gravity. For humans to live in space for a period of time, psychological safety and comfort are just as important as the human necessities, and therefore must be taken into account. This is discussed in *NASA's Space Settlements: A Design Study*[10].

3.0 INITIAL SMART APEX ANCHOR CONCEPT

The initial Smart Apex Anchor will be formed from a satellite. The rolls of Tether are released at geostationary orbit and plaited together while lowering down to the Earth in a similar concept to cassette tapes. As discussed in the 'Road to Space Elevator Era[6]' there are four stages to stabilising the space elevator:

3.1 Stage 1 – Initial Deployment

The Tether is launched to GEO orbit through the use of rockets. The initial step is to assemble the Tether Deployment Satellite in LEO, so multiple launches and orbital assemblies will be required. Once the satellite has been assembled, the mass is raised to geostationary orbit using engines. When the GEO orbit has been reached the Tether is released downwards towards Earth in a single string. The satellite holds 21 reels to provide the initial Tether. As the Tether is deployed, the satellite uses rocket thrusters to increase its angular momentum to balance out the forces. To continue the deployment of the Tether the satellite requires refuelling at GEO. Once the initial Tether has reached the Earth Port terminus, the Smart Apex Anchor and Tether need to be reinforced.

3.2 Stage 2 – Smart Apex Anchor Buildup To Match Tether Mass Buildup

After the initial deployment, the stability control of the Tether is shared between the Smart Apex Anchor and Earth Port. The mass of the Smart Apex Anchor increases proportionally to the mass and strength of the Tether. The mass of the Tether and Smart Apex Anchor will be added in parallel to achieve the required balance for the Space Elevator. When mass, strength and stability of the Tether and Smart Apex Anchor has been optimised, the development of the second space elevator will be initiated to ‘’beat gravity”. The second elevator will probably be constructed at LEO, and once again moved to GEO for deployment. The satellites will then become the initial Smart Apex Anchor. The satellite will have computational, thruster, propellant storage and communication capabilities with the HQ/POC, Earth Port, Climbers and other satellites.

3.3 Stage 3 – Initial Operations Capability

The first mission of the Smart Apex Anchor is to stabilise the Tether. The correct mass and use of thrusters will be needed to adjust the position of the Smart Apex Anchor. The ability to reel in and reel out the Tether as well as off and on loading capabilities from the previous stage, are also essential requirements for the Smart Apex Anchor.

3.4 Stage 4 – Customer Support toward FOC

This stage shows how the customers determine the requirements of the Smart Apex Anchor and where their assets should be delivered. The capabilities of the Smart Apex Anchor, for future space operations should include refuelling, servicing, repairing, construction with the ability for humans to live there. It should also have the ability to release satellites or other objects into the solar system.

4.0 MATERIALS FOR THE SMART APEX ANCHOR

Three concepts on developing the Smart Apex Anchor are discussed in ‘Design Considerations for the Space Elevator Smart Apex Anchor and GEO Node’[11]. All three concepts use the same initial method to launch the Tether into orbit: the satellite is initially launched up to geostationary orbit. As the Tether is deployed downward, the Smart Apex Anchor moves further away from the Earth to act as a counterbalance.

The first concept has no Smart Apex Anchor, just a bare Tether that has a length of over 150,000 km. This maintains the appropriate mass ratio, with the pivot point around geostationary orbit.

The second concept is known as Edwards’ asteroid: it is a proposal that illustrates asteroids as the material mass for the Smart Apex Anchor.

The third concept is satellite deployment. As the Tether is released, the satellite is risen to become the upper terminus and so it becomes the initial Smart Apex Anchor mass. Additional satellites are launched in a similar manner to the first, which are used to reinforce the Tether and to add additional mass to the Smart Apex Anchor. This will need 510 individual Tether reinforcement satellites, to engineer the Tether up to the initial operations capability.

This paper proposes another method, a combinatorial approach consisting of using retired Climbers together with derelict Satellites manoeuvred into position using a *Tug Collection Programme*.

In this concept, the previous satellite deployment (concept 3 above) is used as the base of the Smart Apex Anchor, and additional mass is added by attaching derelict satellites and retired Climbers. By recycling derelict satellites, the Smart Apex Anchor can be grown to the desired optimal mass locally.

4.1 Asteroids

As asteroids are already outside the gravitational pull of the Earth, less energy will be needed to transport them to the anchor. However, they will be difficult to capture, and transport. A bigger issue is that it will be difficult to balance the mass of the asteroid against the requirements of the Tether, and achieving the optimum mass ratio will be elusive.

4.2 Satellites

With satellites, maintaining the optimum mass ratio will be more straightforward. In addition, these satellites can be designed with a Smart Apex Anchor function in mind unlike the Asteroid Anchor. However, the satellite option requires the constant transportation of materials to the Smart Apex Anchor, which is inefficient, and slow. It is calculated that 510 individual launches will be required to reach the optimum mass.

4.3 Climbers

Using Climbers allows the Tether to be reinforced as the Smart Apex Anchor grows in mass, what is more the Climbers could then be used as waste containers to help contain landfill. This too however is inefficient, as 315 six-tonne Climbers are required to build to the optimum mass. It also prolongs the time before the Space Elevator is operating in a useful capacity.

4.4 Derelict Satellites

This approach allows the Space Elevator to reach operational status sooner than all the other methods, and can be achieved without committing the Space Elevator away from operations.

It is straightforward to balance the mass ratio requirements, it allows the Space Elevator to become operational without hundreds of missions, and it will also reduce Space Debris in both Geosynchronous Clarke and Disposal orbits.

However, the collection of derelict satellites will require a *Collection Programme* to capture, retrieve and transport them to the Climber. This then ascends up the Tether to the Smart Apex Anchor, where it and the collected satellites are then assembled into the Smart Apex Anchor structure. To achieve the optimum mass, 95 Climbers [Appendix A] will be required to transport the captured derelict satellites.

The *Tug Collection Programme* can be initiated along with the initial Tether deployment mission, to coincide with the Space Debris cleanup missions that are required prior to Tether deployment.

Another consideration is the condition of the derelict satellites. Satellites with poor structural integrity could hamper a *Collection Programme*, and onboard residual propellants could potentially pose a subsequent threat to the Smart Apex Anchor itself. These issues could be mitigated as part of the *Collection Programme* by employing a local condition survey.

5.0 LOCATIONS AND MASSES OF DERELICT SATELLITES

The build-up of derelict satellites in geostationary orbit is an increasing issue. It risks damaging operational satellites and results in a growing difficulty to launch objects into geostationary orbit. The current solution for derelict, or decommissioned, satellites is to raise them into the disposal orbit, an orbit 200km above the geostationary orbit. This is not a long-term solution, so repurposing them is a useful contribution to this issue.

In 2002, the ESA ROGER[12] stated that the worst-case scenario for space debris is that [sic] '*there could be as many as 1700 satellites in geostationary orbit by the year 2030. 79% of these could be uncontrollable giving a 3.7% risk of collision or a 1 in 25 chance.'*

5.1 The Number and Locations of Satellites

There have been many recent studies calculating the number and size of space debris objects and derelict satellites. Different organisations have developed tracking systems to locate the larger objects, such as ESA's ROGER.

In January 2011[13], NASA recorded that over 900 spacecraft have been launched since 1963 into a geosynchronous orbit together with an additional 200 launch vehicle upper stages.

In 2016, 400 derelict satellites[5] were monitored with another 427 active satellites in this orbit. On decommission, around two thirds[14] of these operational satellites reach the disposal orbit, a quarter fail in the attempt, and the remainder are left in-situ in the geosynchronous orbit.

The probabilities of collisions within the geostationary orbit have been calculated by the University of Colorado according to the paper 'Preserving Geostationary Orbit: the Next Steps[15]'. This is the only study that fully accounts for the longitudinal right ascension of the objects, and the high number of perturbations.

Within the disposal orbit there are 320 intact derelict satellites[16] within a 400km altitude span. An additional 236 intact derelict satellites were discovered in the SEMI orbit within a 6000km altitude span.

5.2 The masses and placements of the different satellites

Although the average mass of a satellite is 1.89 tonnes[17], smaller satellites in the lower orbits are not good candidates for capture for the Smart Apex Anchor. The target derelict satellites are in GEO or in a Disposal orbit above GEO, and have masses of 4 tonnes and upwards. This minimises the work to achieve the Initial Operations Capability of the Smart Apex Anchor.

- 3% of satellites are commercial and have a mass of 6.5 tonnes.
- 13% of satellites are commercial telecommunications and have a mass of 5.5 tonnes.
- 27% of satellites have a mass between 5.5 and 6.5 tonnes.

There are three different classes of satellites. The lowest class satellites have masses between 1.5 and 3.5 tonnes, the midrange class satellites have masses between 3.5 and 5.5 tonnes, and the highest class have masses between 5.5 and 6.5 tonnes.

Using "The Intact Derelict Deposition Study"[16], the combined mass of the intact derelict satellites within the geosynchronous orbit with an altitude span of 400km is 460 tonnes. The derelict satellites within SEMI orbit have a 6000km altitude span and have an additional combined mass of 350 tonnes.

The candidate satellites for the *Collection Programme* are all located within a 300km span within the Disposal orbit.

6.0 TUG COLLECTION SYSTEM

The technique that is being proposed in this paper feeds off the concept presented in the paper 'A study into the sustainable disposal of end of life GEO satellites[14]'. The paper discusses the 'Necropolis' system where geostationary derelict satellites are collected and transported to a long-term storage facility.

The 'Hunter' (retrieval device) uses electric propulsion to increase or decrease velocity to match that of the target derelict satellite, using 4 ion thrusters for more accurate manoeuvres. The Hunter concept uses a stringer system which uses either the apogee boost motor or clamp ring as the physical capture point. The capture mechanism is mounted on the spin table that matches the speed of the satellite, to then release a harpoon to attach the satellite to the Hunter.

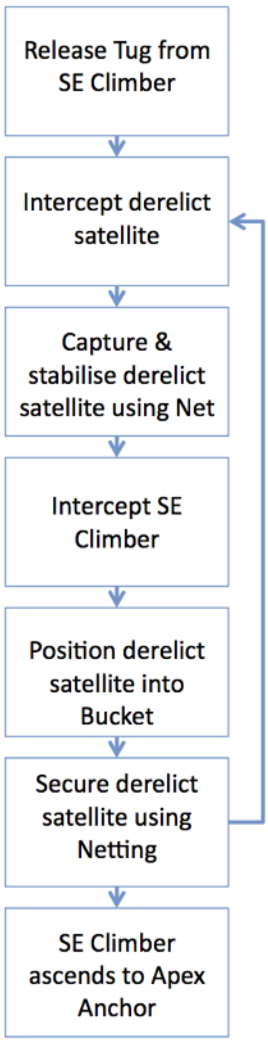
For the Smart Apex Anchor *Tug Collection Programme*, this paper proposes using a Net for the capture mechanism rather than the harpoon. The net is a more efficient way to capture the satellite as the orientation of the collection device does not need to be adjusted. It also mitigates the risk that a satellite might break up into fragments upon impact from a harpoon.

The *Collection Programme Tug* would employ a similar retrieval device to the Necropolis system; however, it would be released directly into orbit from a Space Elevator Climber. The ion propulsion has a higher specific impulse than chemical propulsion methods, is 7-8 times more efficient and so will have a longer operational life.

The *Tug's* collection net is required to be flexible to wrap around the derelict satellite in a controlled manner, to maintain its integrity when towing, and to withstand impacts from space debris.

The elasticity of the design of the Net will reduce the angular momentum of rotating satellites, and rotation will be reduced to acceptable levels by further use of the ion thrusters on the *Tug* spacecraft.

The *Tug* will use a collection net manufactured using the same materials as the Tether. The most suitable material currently being studied is two-dimensional Graphene, printed out in single atomic layers.



The *Tug* will share attributes with the Smart Apex Anchor: a GPS locator, 3D axis stabiliser engines and communication. The Earth Port will control the *Tug* and manage its transfer into orbits to intercept the derelict satellites.

TRANSPORTING MATERIAL TO THE SMART APEX ANCHOR

Each Climber's ascent is controlled from the Earth Port, has a mass of 6 tonnes and can carry a payload of up to 14 tonnes. The Climber is used to transport the derelict satellites up to the Smart Apex Anchor, this allows the *Tug* to perform additional retrieval missions. The resultant mass of the Climber and its derelict satellite payload are added to the mass of the Smart Apex Anchor.

Once the *Tug* has retrieved the derelict satellites, the *Tug* will be programmed to rendezvous with the empty Climber.

The constraints on the Climber payload will be determined by the dimensions/morphology and the masses of the collected satellites. It is essential that the Tether is protected from potentially damaging collisions with the retrieved satellites.

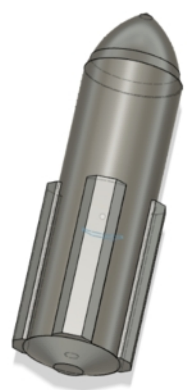


Figure 1- Derelict Satellite Collection (Left)

Figure 2 - TUG

Collection Rocket (Right)

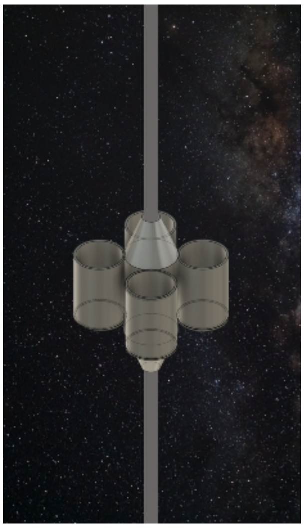


Figure 3 - Climber with Inflatable Buckets (Left)

To maximise the payload of each Climber, inflatable buckets[18] could be attached, containing the derelict satellites, to the external hull of the Climber. Once all satellites have been secured in place, the buckets are wrapped in Graphene netting to protect the Tether and the Climber as it ascends to the Smart Apex Anchor.

This will reduce the number of Climber missions required to achieve Initial Operations Capability.

The higher-class satellites will be the first to be collected to minimise the number of *Tug* retrieval missions.

The paper "A study into the sustainable disposal of end of life geo satellites"[14] has suggested the following list of derelict satellites that should be the first to be collected and redistributed.

Name	Designation	Semi-Major Axis (km)
SKYNET 4b	1988-109a	42 314
SKYNET 1a	1969-101a	42 164
NATO 1	1970-021a	42 163
NATO 2b	1971-009a	42 164
SKYNET 2b	1974-094a	42 171
METEOSAT 1	1977-108a	42 194

Table 1 - Demonstration Mission Target List

The distance between the satellites along the semi-major axis are relatively small especially the distance between NATO 2b and SKYNET 1a, as they lie on the same axis.

Once fully laden with collected satellites, the Climber will then ascend the Tether and attach itself to the Smart Apex Anchor. The entire Climber complete with payload will then be used as additional mass, resulting in up to a 20 tonne increase in mass. So as few as 95 Climbers will be needed to reach the initial operations capability.

THE FUTURE

The Space Elevator will present easy launch capability for the exploration and development of a Solar System wide economy.

Interplanetary craft such as Project Scorpion[7], capable of landing and return in low gravity environments such as the Moon and provide long-term habitats for human missions through the Solar System, would prosper from a Space Elevator infrastructure and could become commonplace.

With the onset of a Solar System wide economy, larger scale projects such as World Ships and potentially interstellar missions such as Project Icarus[8], would for the first time be viable. The Space Elevator could be an essential next step to achieve these.

GAIA data[19] shows that similar interstellar Oort clouds pass through the Solar System's with a mode of 0.5m years. World Ships[20] could easily transfer orbits to other stellar systems without incurring significant costs during these times, and humankind or their successors could populate the galaxy exponentially.

GEO orbits are the ideal location to build large-scale engineering projects such as World Ships. With only 4% of the mass of chemical rockets able to reach this orbit, only the Space Elevator will make these projects technically and economically viable.

There is an argument that the resources available at the Smart Apex Anchor, together with the gravitation effect of the Centripetal force, may be a more suitable environment to manufacture such structures.

CONCLUSION

The Smart Apex Anchor can reach Initial Operations Capability in the shortest time and at the lowest cost by employing the *Collection Programme* proposed in this paper.

The *Collection Programme* uses a small number of *Tugs* to collect derelict satellites from GEO and Disposal orbits. The satellites, collected in Graphene nets, are returned to the Climber. The Climber uses inflatable Buckets to contain the satellites and the structure is secured with graphene netting. The full Climber then ascends to the Smart Apex Anchor.

This proposed technique will reduce space debris, reduce the number of missions required to achieve Initial Operations Capability, and reduce the cost.

APPENDIX

APPENDIX A

The difference between the required Smart Apex Anchor mass for Initial Operations Capability and the deployment satellite.

$$1900-14=1886\,T$$

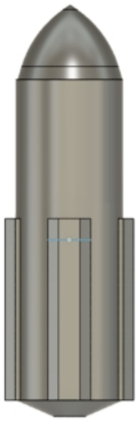
The number of Climbers needed to reach the target mass.

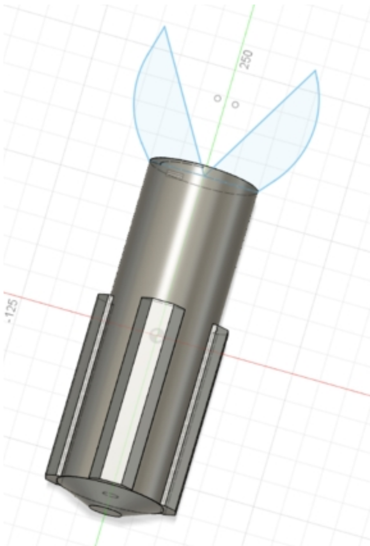
$$\frac{1886}{¿20}=94.3$$

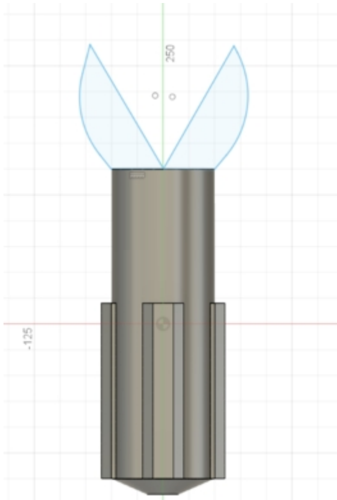
$$¿95\,Climbers$$

APPENDIX B

TUG Designs





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