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Design concepts for the first 40 km a key step for the space elevator

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ABSTRACT

The Marine Node for the Space Elevator Infrastructure is the base for all activities to load and unload the cargo and climbers. As the basic design of the space elevator power system is solar power only, the first 40 km is hazardous to operations and demands enclosed packaging of fragile tether climbers. A significant question is: how do we place a full-up tether climber, driven by solar power, above the atmosphere? Two approaches, starting at the Marine Node, allow the tether climber to initiate the climb with solar energy above the atmosphere. The third viable approach is to provide a platform at altitude for initiation of tether climb. These approaches would enable solar power to be the source of energy for climbing. The three approaches are:

Option One and Two: Marine Node (MN) Starting Location.

MN – Box Protection – use boxes to protect the fragile solar panel and power the climber directly with a power extension cord to climb out of the atmosphere.

MN – Spring Forward – use the characteristics of the elastic factor of the tether material.

Option Three: High Stage One—develop a platform at altitude.

Dangers for the space elevator during the first 40 km in altitude are discussed, and the options to deploy the tether climber and its solar arrays from the ocean surface to the desired altitude are explained.

1. Introduction

The space elevator needs to pass through the Earth's atmosphere so that payloads can be raised from the surface. However, the atmosphere is turbulent, with strong winds, ice and electric storms at many altitudes. A wise choice of location can reduce these effects, but not eliminate them. For example, the area of the Pacific to the west of the Galapagos Islands has experienced no hurricanes since records began in the 19th century. The anchor point at which the space elevator reaches the ocean is called the *Marine Node*.

Above the atmosphere, the tether extends to the *Apex Anchor*, 100,000 km from Earth. The tether is designed as a thin ribbon one meter wide, curved to minimize damage from meteors and space debris. Within the atmosphere, a narrower ribbon of 20 cm has been proposed to reduce the effects of winds [1].

The tether climbers are to be powered by lightweight solar panels, and they will require protection in the atmosphere. One solution is to fold the solar panels and enclose them in a container. This method is called *box protection*. An alternative source of power is required while the solar panels are folded. Since this is only necessary for

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a few tens of kilometers, a lightweight power cable can be used without adding substantially to the weight.

A second method of powering the tether climbers while the solar panels are folded is to exploit the elastic properties of the tether. A modest variation in its tension will create sufficient force to lift a tether climber above the atmosphere, where it can unfold its solar panels and continue ascending under its own power. Once the tether climber has ascended for several hours and is safely out of the way, the Marine Node can pull the tether down in readiness for lifting another climber the next morning. This method is called *Spring Forward*.

A third method, known as *High Stage One*, is to anchor the tether to a platform at high altitude. The platform is supported using an adaptation of the Lofstrom Loop [2]. Inside evacuated tubes, a continuous stream of *rotors* travels from the surface up to the platform and down again. Deflecting the rotors creates a levitation force that holds up both the tubes and the platform. At the surface, the rotors travel round a horseshoe-shaped structure called an *ambit* so that they can travel up to the platform again and continue indefinitely. Magnetic levitation is used to minimize friction. High Stage One is designed to absorb wind and other atmospheric hazards without affecting the tether. Tether climbers can be kept above most of the atmosphere so as to protect their solar panels.

2. Marine node

A likely basis for the Marine Node will be an oil exploration or drilling ship. It will have living facilities and power generation. It will house telemetry, tracking and command systems, and will process satellites and other payloads prior to space launch. It will need aircraft facilities, which could take the form of a floating airport to handle regional jets flying in from the nearest mainland. It may be better to operate a helicopter shuttle from Galapagos. For example, the Super Puma helicopters used in the North Sea have a range of 700 km, and drilling ships have suitable helipads.

The preferred site is in the Pacific within helicopter range of the Galapagos.

Although this area is meteorologically calm, there is still plenty of high-altitude wind and other hazards, such as ice and electric storms. Therefore, measures are needed to protect the tether climbers.

2.1. Box protection

A container would protect a climber's fragile solar panels from wind, ice and electric storms. It could be lifted by the tether climber's own mechanism, or it could have a separate climbing mechanism. An advantage of a separate mechanism would be to give greater flexibility in the tether design. To reduce the effects of winds, the tether in the atmosphere is narrower than the one meter width it has in space. It could be even narrower than 20 cm so long as it has the necessary cross section of 10 mm^2. However, the main tether would have to support the extra weight of the box with its climbing mechanism.

Power for the box protection could be supplied from a cable connected to the surface. Carbon nanotubes can be made to act as conductors, semi-conductors and insulators. Hence they can form a very light power cable for the box protection up to the required altitude of at least 40 km. At this point, the box releases the tether climber to continue under its own solar power, while the box returns to the surface.

2.2. Spring Forward

Spring Forward has the advantage that the power is built in to the elasticity of the tether, which provides the propulsion. Effectively, the energy is stored when the Marine Node stretches the tether by reeling it in. An extension of 0.1% permits a length change of 100 km. A protective box will be necessary for the fragile solar panels. There will be variations in tension that will be transmitted up the tether all the way to the Apex Anchor. Happily, it was shown many years ago that there is natural damping of the resultant longitudinal oscillations [3]. Of course, the tether must be strong enough to cope with these forces, including the weight of the protective box.

At the required altitude, at or above 40 km, the protective box must remove itself from the tether climber to allow the climber to continue under its own power. The box must return to the surface.

3. High Stage One

This option for the space elevator Earth terminus takes the complexity of traveling through the atmosphere off the tether and places it on an Earth-based structure 30–50 km high. To find the optimal altitude, much further work is needed on the solar panel design for the tether climbers. The stresses induced by the lower and upper atmospheres are dealt with by infrastructure based firmly on the Earth's surface. The space elevator is able to deal with the effects of Earth's turbulent atmosphere without adding substantially to the weight that has to be supported from geosynchronous orbit. High Stage One achieves this by keeping the tether in and above the mesosphere. If the tether went down to the surface it would have to cope with wind pressure in the lower atmosphere. Using guy wires for stabilization or increasing the tension in the tether will cause strong variable forces that would have to be supported from the top. In addition, there are the hazards of ice and electric storms.

The concept is to place the working end of the tether on a firm platform at altitude. This facility would be capable of supporting 3000 t at 40 km altitude with no forces on the tether. The Lofstrom Loop ensures stability of the platform at altitude and provides routine access from the ocean surface to 40 km altitude using electric cars similar to a funicular used on mountains today [4]. This transfer of hazards and forces from the lower portion of the space elevator infrastructure to the terrestrial based Lofstrom Loop simplifies the problem and reduces the mass requirement of the space elevator tether. Once the platform has been established at 40 km altitude and the logistics "train" has geared up, the space elevator infrastructure becomes safer and simpler.

The basic principle is to create an upward levitation force on the high-altitude platform by using magnetic forces to change the direction of the momentum vectors of the rotors as they travel past. Friction is very low because the rotors travel in a vacuum inside the tubes and use a method of magnetic levitation employing permanent magnets stabilized by electromagnets under electronic control. A similar method of levitation is used in some machines, including vacuum pumps. Electronic controls can be built with extremely fast response times and low voltages, leading to very low power consumption and high reliability.

To support a platform at 40 km altitude, the rotors need to travel at about 1.6 km/s. The structure is shown in Fig. 1.

3.1. Surface stations

High Stage One can be built on land or at sea, but there are good reasons to prefer the high seas because of favorable climate and political considerations. Two surface stations about 112 km apart are needed for a platform at 40 km. These are supported by floating platforms, as illustrated in Fig. 2.

Rotors travel round an ambit and enter a straight section where their speed can be boosted to make up for any losses. Next, the rotors descend a little below the ocean surface and are directed up the ramp, where their angle of ascent is adjusted to the required inclination of about 50° to the horizontal. In effect, the ramps bear the entire weight of the structure, and there is no load on the tether. As the rotors rise, they exert a levitation force perpendicular to their direction of travel, that is, perpendicular to the direction of the tube. Hence they lose kinetic energy to gravity alone, and they regain this as they descend. As they rise, the levitation forces cause their inclination to reduce. At the top, the force needed to sustain the platform causes them to turn downwards, and they continue their descent to the second surface station. There they pass through the ramp, the ambit and back to the ramp where they rise once more and repeat the cycle in the opposite direction, continuing indefinitely.

Thus the tubes are in pairs, with one containing ascending rotors and the other descending. Several pairs of tubes are desirable, so that one pair can be stopped for service and maintenance while the others continue to support the platform. To support a platform of 3000 t, six pairs of tubes are proposed, five pairs to carry the weight and one in reserve for maintenance. There are more details elsewhere [5].

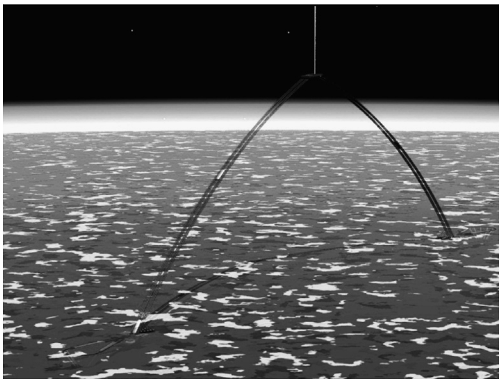

Fig. 1. A loop with the platform at high altitude anchoring the tether.

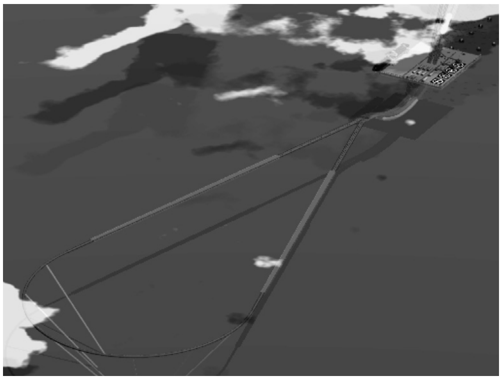

Fig. 2. A surface station with ambit.

3.2. Advantages

Strong winds are sometimes experienced in the upper atmosphere. The significant factor for the space elevator is the wind pressure, i.e., the force per unit area. Fig. 3 contains estimated maxima.

High Stage One protects the tether and the climbers' solar panels from these forces by keeping them above most of the atmosphere. Winds on the tether cause it to blow about, which increases its tension. The upper part of the tether – up to the Apex Anchor at 100,000 km altitude – has to support this tension, and this entails making it more massive. Moreover, winds are variable and the upper tether would have to absorb the variations. Instead, High Stage One transmits these forces down to the Earth's surface. The following table shows the advantage of having the platform at or above 40 km altitude. There is a factor of nine saving compared with taking the tether down to sea

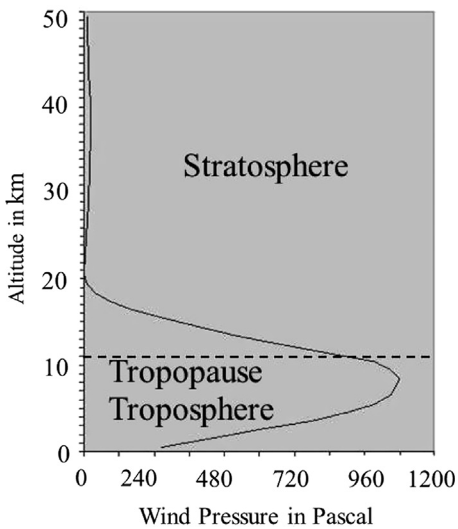

Fig. 3. Estimated maximum wind pressure in the upper atmosphere.

level. These figures are based on the assumptions in the book by Edwards of a tether 20 cm wide allowed to blow up to 10° out of the vertical [1].

Platform Altitude (km)	Estimated maximum wind force on tether (kN)	Tension in tether due to wind (kN)	Total tether tension at platform (kN)	Estimated total tether mass (metric tons)
0	590	3400	3830	66,000
10	210	1210	1555	27,000
15	50	290	630	10,900
20	25	145	485	8,300
30	22	125	465	7,900
40	12	70	410	7,000
50	5	30	370	6,300
80	0.015	0.09	340	5,800
100	0.00022	0.001	340	5,800

Ice is a hazard up to about 12 km altitude. The weight of deicers would add about 5 t to the weight that the tether must support, and High Stage One relieves it of this burden.

Since High Stage One stands on the Earth's surface, it can be developed and tested in parallel with activity on designing the tether, tether climbers and other components. A step-by-step development approach is outline below (see Section 3.5).

Protecting the tether from gusting winds makes it easy to move the tether when required to avoid space debris.

3.3. Avoiding space debris

Moving the tether is easier in the thin air at high altitude than at the surface. Because of the negligible air resistance, it is possible to swing the tether by pushing a 5-t weight sideways at the base, which is on the high-altitude platform. The forces and movement are illustrated in Fig. 4. The base can be swung 20 km in about 9 min in any horizontal direction, and this movement is propagated up the tether at a speed between 2 and 5 km/s, depending on the tension, which varies with the altitude of the payload.

Although there are winds up to 100 km altitude, they will not materially affect the tether owing to the extremely tenuous atmosphere.

When the maneuver is complete, wires attached to the tether base are used to drag it back to the central position. Alternatively, it is possible to arrange to drag the base both ways, out and back, rather than swinging it.

3.4. Stability

A significant amount of work has been done on stability in the presence of variable winds. A method has been developed called *active curvature control* to take advantage of the strong forces generated by rotors traveling round even quite slight bends. This has been proved viable using mathematical analysis and computer simulation [6].

The method is to take advantage of the bending that occurs in a tube when subject to wind but to limit the bending to just that required to counteract the wind force. The effect is to propagate movement down each tube to the surface station, where guy wires will absorb the resultant forces [4].

3.5. Prototyping and development

Work is in progress to produce detailed design documents and prototype components. Beyond that, it is proposed that development should proceed through a series of models of increasing height:

- 10 m indoors with a pair of evacuated tubes.
- 60 m outdoors in a field, testing stability in winds.
- 1 km verifying the viability of a very tall land-based structure—this is as tall as the highest building currently planned, the 1 km tower in Kuwait.
- 5–20 km at sea—a test of all the techniques needed to build High Stage One at close to full scale.

Two development schedules have been produced, leading to the production of a structure 40 km above sea level. One schedule takes 17 years and appears in Fig. 5. The associated cost estimates in millions of U.S. dollars year by year are given in the table below.

Years from start	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Cost	0.1	0.3	0.2	0.5	0.8	1	2	5	6	10	120	80	60	210	700	500	400

There is an alternative, more aggressive, schedule taking 12 years which assumes a faster build-up of funding and development teams but involves a similar total cost of about $2 billion.

4. Conclusions

High Stage One simplifies the design of the tether and tether climbers by dealing with atmospheric hazards such as winds and ice independently and transmitting the forces down to the surface. It uses commonly available materials, including Kevlar. Magnetic levitation is a proven technology. Its use for dynamically supporting a structure is well researched but still immature, and so a prototyping and development schedule has been given to make it ready for use as part of the space elevator.

Assuming successful tests, this is the preferred solution, but Box Protection and Spring Forward are also viable options for protecting the tether climbers from Earth's turbulent atmosphere.

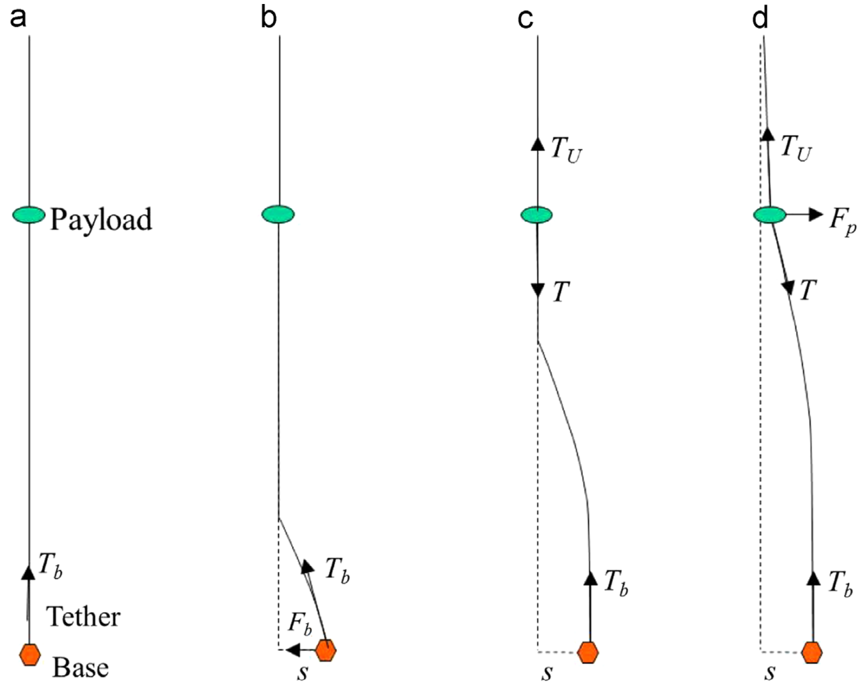

Fig. 4. Tether positions when swinging the base to avoid space debris.

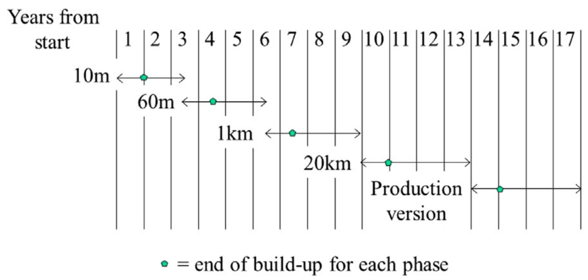

Fig. 5. A development schedule for High Stage One.

Acknowledgments

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