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DISPOSAL OF GEOSYNCHRONOUS SATELLITES BY EARTH-ORIENTED TETHERS

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Abstract

An extended-length gravity-gradient-stabilized geosynchronous tether system is described that can be used to collect and dispose of space debris objects in geosynchronous Earth orbit (GEO). The debris objects are released from the tether at various distances from GEO for deployment to escape or Earth reentry type trajectories. Tether length, mass, and counterweight (upper and lower tip mass) requirements are determined for Kevlar and carbon nanotube materials. Tether extension to the Earth surface is examined (the space elevator concept) for the carbon nanotube material and the relevant design parameters established.

1. INTRODUCTION

Although the present annual collision probability for average operational spacecraft in GEO is only on the order of 10^{-5} it is considered necessary to limit future accumulation of space debris to minimize the collision hazard in the future. All current methods for object disposal in GEO involve the expenditure of propellant either to maneuver satellites at their end-of-life above the geostationary altitude or to use a dedicated space tug, which could rendezvous and collect dead objects for deorbit. An alternative approach, which eliminates or greatly reduces the need for propellant expenditure for debris removal is the application of the momentum exchange tether-based systems.

The well-known space elevator concept could be used for this purpose, or a shorter variant of it, as described in this study, is an even more practical application of the tether-based momentum exchange system. It can be designed to remove debris objects from GEO without expenditure of any propellant other than that required to rendezvous with non-cooperative debris objects and deliver them to the tether-based system for disposal.

The advantage of the GEO-based tether system over that of the space elevator is its significantly reduced mass, size, and the ability to maneuver via momentum exchange, if necessary. This is accomplished by reeling in the tethers above and below the GEO altitude in order to transfer the attitude momentum to orbital momentum. Also, the collision risk in GEO is much lower than that at low altitudes where the space elevator is more vulnerable. The absence of the radiation belts in GEO is similarly a considerable advantage for the GEO tether system compared to the space elevator concept.

The principal issues to be resolved are those related to the collection of space debris in GEO. Even though the GEO space tether can be placed in any desired GEO location and relocated as needed by reeling in and out the tethers, it can also be deployed in the invariant plane (at about 7° to the equator) where it will not be subject to the sun/moon perturbations as much as at other inclinations. Moreover, future missions may be designed to rendezvous the rocket stages with the tether station for disposals. Another possibility is the use of a free-flyer debris collector, which can rendezvous with noncooperative objects and deliver them to the tether station for disposal.

These and other approaches to the debris collection procedure must be examined and assessed regarding practicality, cost, and efficiency before a viable design of the tether collection system can be defined.

The first mention of a space tower and geosynchronous altitude equatorial orbit (GEO) appeared in a 1895 book by K. E. Tsiolkovski. In the 1959 re-publication,[1] Tsiolkovski reveals his thoughts about a science fiction voyage through the universe and talks about different physical phenomena, including the idea of an artificial satellite of the Earth. A space tower is described, which when located in the equatorial plane of a planet, experiences decreasing gravity with altitude, becoming zero at 5.5 Earth radii. The idea of a space elevator is later described by Y. N. Artsutanov, who proposed a bootstrap construction of a cable from geosynchronous altitude to the Earth surface.[2] His "cosmic lift" or a "heavenly funicular" was calculated to be able to deliver 500 tons an hour to orbit. A. C. Clark[3] examined the concept in detail and showed that only a cable material with an "escape length" of 5000 km could support such an elevator. This meant that a material strong enough to hang 5000 km under sea-level gravity would be required for the elevator. No such material was available until recently when carbon nanotube was discovered. The carbon nanotube material is estimated to have a tensile strength of 130 GPa compared to <5 GPa for steel and 3.6 GPa for Kevlar. The density of the carbon nanotubes is 1300 kg/m^3 compared to 7900 kg/m^3 for steel and 1440 kg/m^3 for Kevlar, which makes it an ideal material for the space elevator.

Sutton and Diderich[4] consider a satellite system that is synchronous using a long, tapered cable that extends toward the Earth with a satellite attached at the end of the cable. They showed that for a boron steel material (with a tensile strength of 500,000 psi and density of 2.4 g/cm^3), a satellite may be suspended at an altitude halfway between GEO and Earth requiring a mass of a cable and counterweight of about 85 times that of the suspended satellite mass.

Chobotov[5] extended the results of Sutton and Diderich using a viscoelastic organic material Kevlar that has nearly twice the strength-to-weight ratio of boron steel. It showed that the mass of the cable and counterweight is on the order of 25 times that of the suspended satellite at halfway to the GEO altitude.

Pearson[6] re-examines the space elevator concept and shows that it can be used to launch probes by extracting energy from the Earth's rotation. Penzo[7] applies the same principle to transport satellites to different orbits by using long gravity gradient stabilized tethers in space.
B. C. Edwards[8] describes the design and deployment of a space elevator using a carbon nanotube tape and discusses how the various problems of the space elevator concept can be solved using current or near-future technology.

The present study examines the momentum exchange capability of a geosynchronous tether satellite system to dispose of (i.e., reorbit) a dead satellite in GEO. The satellite disposal system consists of a geosynchronous satellite (base) from which long tethers are extended up and down along the local vertical. The tether is in tension due to the difference of the gravitational and inertial forces acting along the local vertical. A spent satellite or a debris object can be grappled by the base satellite and allowed to slide up or down the tether for release at a selected distance from GEO. The resulting orbit of the released satellite may be on an Earth reentry trajectory (when released at the lower altitude) or an escape orbit if released at the upper end. Simultaneous release of two or more objects can be used to balance the angular momentum of the tether satellite system and thus maintain its geosynchronous orbit.

A change of longitude (i.e., repositioning) can be performed either by a small thruster attached to the base or by a transfer of the system attitude angular momentum into orbital momentum. The latter can be accomplished by collapsing (i.e., reeling in) the upper and lower tethers into the base satellite. This results in an increase of the center of mass orbital velocity in a higher energy elliptical orbit. Re-extending the tethers again after several revolutions in the new "phasing" orbit will return the base satellite to GEO at another longitude.

The study considers the length, mass, and tether cross-section requirements for the debris disposal tether system deployed in geosynchronous orbit. Two tether materials are used: Kevlar with a design strength of 3.66 GPa (530,700 psi) and a carbon nanotube material with a strength of 100 GPa (14,500,000 psi).

Extension of the tether to the surface of the Earth (the space elevator concept) is shown to be theoretically feasible with the use of the carbon nanotube material for the tether.

2. PRINCIPLE OF OPERATION

Consider a schematic representation of a GEO debris disposal system as shown in Figure 1.

The Tether Satellite system deployed in GEO consists of the base satellite and two tethers with end masses deployed along the local vertical downward and upward from GEO. The system can be located either at stable or the unstable longitudes. If an unstable longitude is selected, the system will have a slow drift and may thus encounter all objects in GEO with time. Once a debris object DB1 is located and collected by the base satellite (by grappling or other means) it is given a slight impulse downward along the tether so that it begins sliding under the influence of the gravitational and the inertial accelerations. These are the accelerations that keep the radially deployed tether in tension. Simultaneously, another debris object DB2 is collected by the base satellite and is given an upward impulse to initiate the slide of the object up and away from GEO. At the end of the tether the counterweight mass M_2 stops the object motion. When both debris objects are at their end masses, they are released from the tether simultaneously. The lower object re-enters the Earth atmosphere in a short time while the upper object is injected into an escape trajectory from the Earth. The tether satellite system will remain in GEO or will acquire a slight drift rate relative to GEO due to the conservation of angular momentum of all satellites. The drift may be used to locate additional debris objects to be released as before. By proper balancing of the debris object masses, the system drift rate relative to GEO can be controlled.

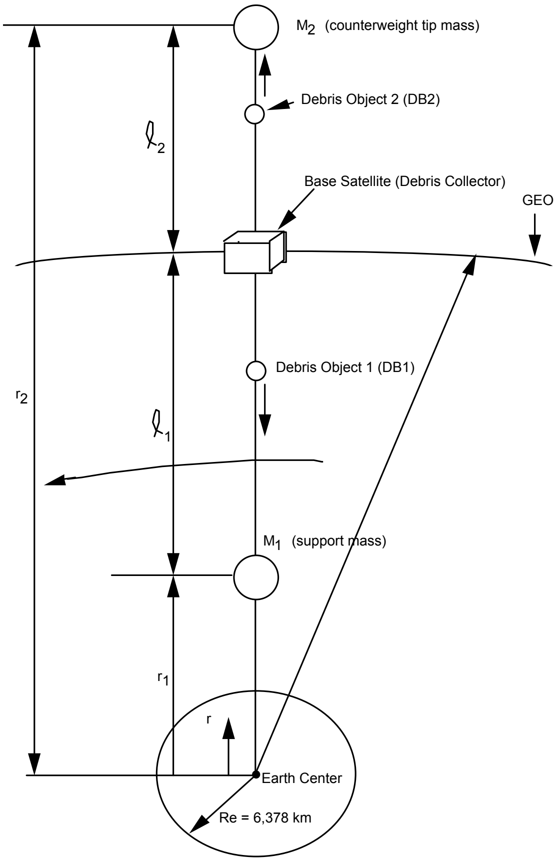

Fig. 1: System Schematic Diagram

3. SYSTEM REQUIREMENTS

For the GEO tether system to perform as described, the configuration parameters must be determined. The primary requirement is the tether lengths ℓ_1 and ℓ_2 for the release of the GEO debris objects DB1 and DB2. This can be determined as follows.

3.1 Earth Re-entry

The determination of the perigee altitude after release of DB1 at the radial distance r_1 is obtained from the solution of angular momentum and energy relations for a two-body system. Thus,

$$h = r_a v_a = r_p v_p = \text{const.} \tag{1}$$

$$\varepsilon = \frac{v_p^2}{2} - \frac{\mu}{r_p} = \frac{v_a^2}{2} - \frac{\mu}{r_a}, \tag{2}$$

where

h = specific angular momentum of released object orbit

ε = specific energy of released object orbit

$v_a = r_a \omega$

$= (\lambda - \ell_1)\omega$

= apogee velocity of released object orbit

$r_a = r_1$

= apogee radius of released object orbit

v_p = perigee velocity of released object orbit

r_p = perigee radius of released object orbit

μ = earth gravitational constant

The solution for r_p can be expressed as

$$r_p = s_1 \lambda \frac{\left(1 - \sqrt{1 - (2 - s_1^3) s_1^3}\right)}{2 - s_1^3}, \tag{3}$$

where

$s_1 = r_1/\lambda$

$\lambda = 42164$ km

=GEO radius

A plot of Eq. (3) is shown in Figure 2.

Thus, for example, if $s_1 = 0.7$ $r_p = 6109.6$ km, which is less than the radius of the Earth $R_e = 6378$ km, ensuring re-entry of DB1. The corresponding $r_1 = \lambda s_1 = 29515$ km.

3.2 Escape Trajectory

The release of DB2 at the upper end of the tether will place it on an Earth escape trajectory.

The release of DB2 at r_2 will become the perigee of the resultant orbit with apogee radius at infinity. The value of r_2 for this case can also be found from Eq. (3) by replacing r_p by r_a and s_1 by s_2, where $s_2 = r_2/\lambda$. Thus, r_a becomes infinite if the denominator in Eq. (3) is set to zero.[9]

Then,

$$2 - s_2^{\,3} = 0 \tag{4}$$

which yields

$$s_2 = 1.26$$

$$r_2 = \lambda\, s_2 = 53127 \text{ km}$$

The total length of the tether system is therefore

$$L = r_2 - r_1 = 23612 \text{ km}$$

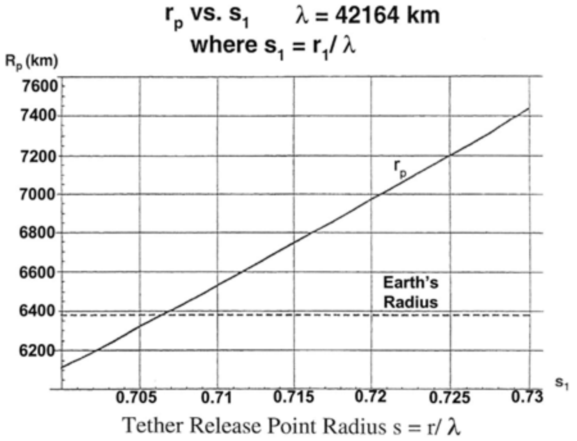

Fig. 2: Satellite Perigee Radius vs Tether Release Point Radius.

$$\ell_1 = \lambda - r_1 = 12649 \text{ km}$$

$$\ell_2 = r_2 - \lambda = 10963 \text{ km}$$

3.3 Repositioning in GEO

The change of longitude (i.e., repositioning) of the base satellite system in GEO may be accomplished by collapsing (reeling in) the upper and lower tethers as well as a low thrust application approach, if necessary. The reeling in of the tethers results in an increase of the center of mass (CM) orbital velocity since it is non-coincident with the system center of gravity (CG). This effect has been evaluated by V. V. Beletski[10] for a dumbbell type satellite oriented along the local vertical as

$$V^2 = \left[\frac{1+\alpha^2}{(1-\alpha^2)^2}\right] V_0^{\,2}, \tag{5}$$

where V_o is the GEO circular velocity.

$$\alpha = \ell / \lambda,$$

and where ℓ is the half length of the dumbbell (tether), considered massless except for masses at the ends of the dumbbell (tether). For this case $\alpha \approx \ell / \lambda = 0.28$. The system center of mass orbital velocity then becomes

$$V = 1.127 V_0.$$

The increased velocity of the CM results in an elliptical phasing orbit with a period of revolution greater than 24 h. Re-extending the tethers (upward and downward from the base satellite) reestablishes the GEO altitude for the tether satellite system at another longitude.

3.4 Material Properties Effect on Tether Tension

The tether equilibrium equation[4–6] for example is

$$\frac{dT}{dr} = \rho A \left(\frac{\mu}{r^2} - \omega^2 r\right), \tag{6}$$

where

T = tether tension

ρ = tether mass density

A = tether cross-sectional area

μ = Earth's gravitational constant

ω = Earth's rotation rate

r = radial distance from Earth center

Integration of Eq. (6) yields the tension in the tether normalized by its maximum value T_m at GEO.

Thus,

$$\frac{T}{T_m} = e^{-\gamma(1-s)^2\left(\frac{1}{2}+\frac{1}{s}\right)} \tag{7}$$

where

$$s = \frac{r}{\lambda}$$

$$\gamma = \frac{\rho}{\sigma}(\mu\omega)^{2/3}$$

σ = tether allowable stress

In order to minimize maximum tension T_m in Eq. (7), γ should be minimized. This indicates that ρ should be minimized and σ maximized. The ρ/σ ratio thus defines the structural characteristic of the tether. For Kevlar $\rho = 1440$ kg/m^3 and $\sigma = 3.6$ GPa, therefore,

$$\left(\frac{\rho}{\sigma}\right)_k = \frac{1440}{3.6\text{GPa}}\frac{\text{kg}}{\text{m}^3}$$

$$= 400 \text{ x } 10^{-9}\left(\frac{m}{s}\right)^{-2}$$

which yields

$$\gamma_k = \frac{\rho}{\gamma}(mw)^{2/3} = 400 \text{ x } 10^{-9} \text{ x } 9.45 \text{ x } 10^{6} = 3.78.$$

which is close to $\gamma = 3.81$ as used in Ref. 5 for the 3.6 Kevlar material. This value ($\gamma = 3.81$) for Kevlar is therefore assumed in this study.

For the carbon nanotube material $\sigma = 100$ Gpa, and $\rho = 1900$ kg/m^3 (Ref. 11). Thus,

$$\left(\frac{\rho}{\sigma}\right)_{cn} = \frac{1900}{100 \text{ x } 10^{9}}$$

$$= 1.9 \text{ x } 10^{-8}(m/s)^{-2}.$$

Therefore,

$$\gamma_{cu} = \left(\frac{\rho}{\sigma}\right)_{cn}(\mu\omega)^{2/3}$$

$$= 1.9 \text{ x } 10^{-8} \text{ x } 9.45 \text{ x } 10^{6} = 0.18$$

3.5 Tether and Tip Mass

For constant stress on the tether, the tether cross-sectional area is a function of radial distance. It is

$$A = \frac{T}{\sigma}.$$

The tether (cable) mass is given by

$$M_c = \int_{r_1}^{r_2}\rho A dr = \int_{r_1}^{r_2}\rho\frac{T}{\sigma}dr.$$

The ratio of the total tether mass M_c to the suspended mass M_1 is given (Ref. 4) as

$$\frac{M_c}{M_1} = \gamma\left[\frac{1}{s_1^2} - s_1\right]e^{\gamma(1-s_1)^2\left(\frac{1}{2}+\frac{1}{s_1}\right)} \text{x} \int_{s_1}^{s_2} e^{-\gamma(1-s)^2(1/2+1/s)}ds, \tag{10}$$

where

$$s = r/\lambda, \qquad s_1 = r_1/\lambda, \qquad s_2 = r_2/\lambda.$$

The ratio of the counterweight tip mass M_2 to that of the suspended mass M_1 is given by the equation[4]

$$\frac{M_2}{M_1} = -\frac{\left(s_1^{-2} - s_1\right)\exp\gamma\left(1-s_1\right)^2\left(1/2+1/s_1\right)}{\left(s_2^{-2} - s_2\right)\exp\gamma\left(1-s_2\right)^2\left(1/2+1/s_2\right)}. \tag{11}$$

3.6 Terminal Velocity for sliding Debris Objects.

A captured debris object of mass M_d in GEO is subject to a net upward force

$$F = M_d\left(r\omega^2 - \frac{\mu}{r^2}\right). \qquad (12)$$

The terminal velocity v_2 at the upper end of the tether at r_2 can be found from the relationship

$$\frac{1}{2}M_d v_2^2 = \int_{\lambda}^{r_2} F \bullet dr\,, \qquad (13)$$

which yields

$$v_2 = \omega\sqrt{\left(r_2^2 - \lambda^2\right) - 2\mu\left(\frac{1}{\lambda} - \frac{1}{r_2}\right)}. \qquad (14)$$

For $r_2 = 1.26\lambda$, $v_2 = 1.29\text{km/s}$,

such a terminal velocity would be too high and would have to be controlled (by friction or other means) to prevent undesirable effects on the tether.

3.7 Tension and Mass Ratios

Equation (7) is plotted in Figure 3 for Kevlar and the carbon nanotube materials. The results indicate that the maximum Kevlar tether tension in GEO is 0.97/0.52 or 1.86 that for the carbon nanotube material. This requires a correspondingly greater tether cross-section for Kevlar, which is also affected (increased) by the lower design stress (3.6 used for Kevlar compared to 100 GPa for carbon nanotube). The net result is a significantly larger tether mass for Kevlar compared to that of carbon nanotube as can be seen from Figure 4. The ratio of Kevlar tether M_c to that of carbon nanotube at s_2 = 1.26 (r_2 = 53127 km) is on the order of 4.8/0.14 or 34.3. Thus, the Kevlar tether mass is about 34.3 times that of carbon nanotube mass. The ratio of the tip masses M_2/M_1 for the two materials can be obtained from Figure 5, which shows the variation of this ratio, Eq. (11), as a function of distance above GEO to r_2. At r_2 the ratio of Kevlar to the carbon nanotube is about 1.5, which indicates that the Kevlar tether requires a larger tip mass than that for the carbon nanotube material.

Finally, the overall or total mass ratio of the system with respect to the suspended mass M_1 is shown plotted in Figure 6 for Kevlar and carbon nanotube materials, respectively. This plot shows that the overall (total) mass for the Kevlar tether system is about 8/2.3 or 3.48 times that of the carbon nanotube material. It does not appear to be

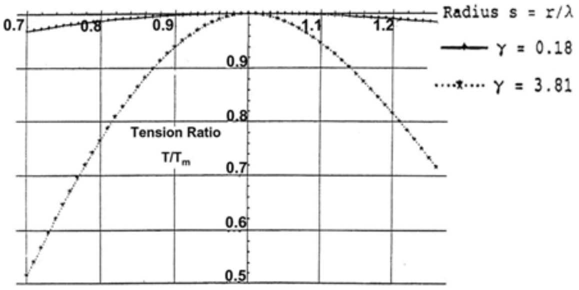

Fig. 3: Tether Tension Ratio vs Radius.

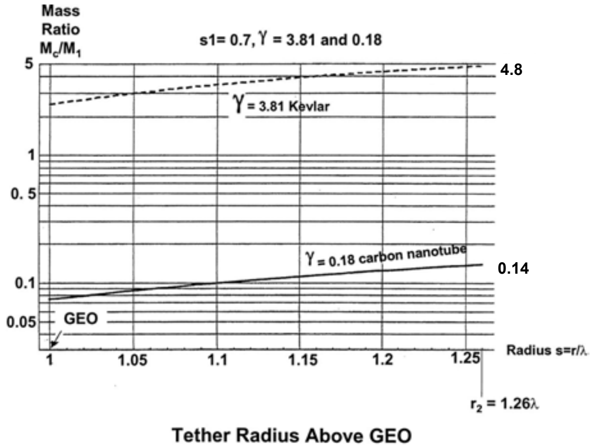

Fig. 4: Tether Mass Ratio vs Radius.

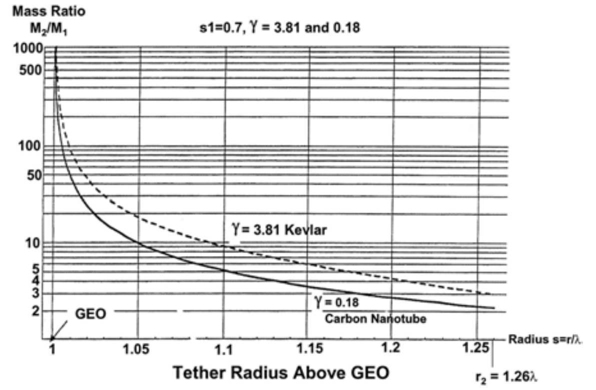

Fig. 5: Tether Counterweight Mass Ratio vs Radius

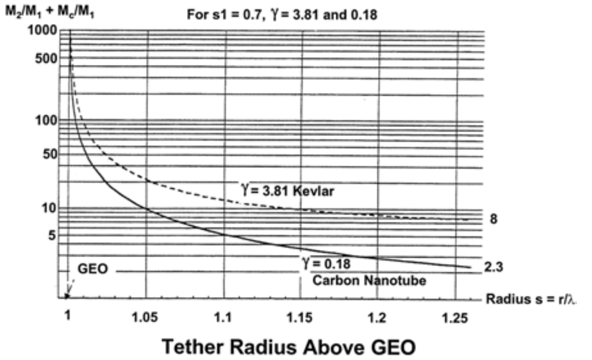

Fig. 6: Total System Mass Ratiio vs Radius.

an unrealistic mass increase for the Kevlar tether system, suggesting that it could be a material of choice for the GEO debris disposing system.

3.8 Kevlar Diameter and Mass Requirements

The primary purpose of the suspended mass M_1 and of the corresponding tip (counterweight) mass M_2 is to maintain sufficient tension in the tether to slide the captured debris objects along the tether, for release at the ends of the tether. Thus, for example, the tension at r_1 to support the mass M_1 is

$$\begin{aligned} T_1 &= M_1\left(\frac{\mu}{r_1^2} - r_1\omega^2\right) \\ &= M_1\lambda\omega^2\left(\frac{1}{s_1^2} - s_1\right). \qquad (15) \end{aligned}$$

For $M_1 = 10000$ kg at $s_1 = 0.7$, $T_1 = 3000$ N.

By Eq. (7), $T_1/T_m = 0.516$ at $s_1 = 0.7$ for Kevlar. Therefore,

$$\begin{aligned} T_m &= T_1 / 0.516 \\ &= 5820\text{N} \\ &= \text{maximum tension at GEO} \end{aligned}$$

The maximum cross-sectional area of the tether in GEO is, for $\sigma = 3.6$ Gpa,

$$\begin{aligned} A_m &= \frac{T_m}{\sigma} \\ &= 1.62(\text{mm})^2. \end{aligned}$$

The maximum diameter is

$$\begin{aligned} D &= \sqrt{\frac{4A_m}{\pi}} \\ &= 1.43 \text{ mm.} \end{aligned}$$

Using a 2-mm-dia tether in GEO as a factor of safety, the tether diameter at M_1 is

$$\begin{aligned} D_1 &= 0.516 \times 2 \\ &\approx 1 \text{ mm.} \end{aligned}$$

To guard against micrometeoroids and small space debris particles the tether could be a Kevlar tape perhaps 10 cm wide and 0.02 mm thick. The tether mass (total) M_c is given in Figure 4 at r_2 as about 4.8 M_1 or 48000 kg. The counterweight M_2 at r_2 is found from Figure 5 as $3M_1$ or 30000 kg.

The total Kevlar tether and counterweight mass is therefore

$$\begin{aligned} M_T &= M_1 + M_2 + M_c \\ &= 88000 \text{ kg.} \end{aligned}$$

This mass is reduced by about a factor of 3.5 for the carbon nanotube tether material.

4. THE SPACE ELEVATOR CONCEPT

The results for the space elevator are obtained by evaluating Eqs. 7, 10, and 11 for $s_1 = R_e/\lambda = 0.15$, and $\gamma = 0.18$ for the carbon nanotube material. The $s_1 = 0.15$ value indicates that the tether is extended from GEO to the Earth's surface. The results are shown plotted in Figures 7 and 8.

Figure 7 shows the tether tension ratio from the Earth's surface (s = 0.15) to GEO (s = 1) for two materials, $\gamma = 0.18$ (carbon nanotube) design stress $\sigma = 100$ GPa, and $\gamma = 3.81$ (Kevlar). From this figure, it is clear that Kevlar is not an acceptable material since T/T_m is an extremely small value near the Earth surface, thus indicating an impractically large value for T_m (maximum tension) at GEO. The carbon nanotube result suggests a reasonable T_m value for $\gamma = 0.18$.

Figure 8 shows the tip (counterweight) mass as a function of r_2. Thus, at s = 2 (r_2 at twice GEO radius) M_2/M_1 is on the order of 50. The total system mass (tether and the end masses) is indicated for the carbon nanotube 100 GPa material at $s_2 = 2$ on the order of about 90 times the suspended mass, M_1. Thus, if $M_1 \approx 1000$ kg at the Earth's surface, the total tether and tip mass is on the order of 90000 kg. Such a mass requirement appears to make the space elevator construction practical when using the carbon nanotube material for the tether.

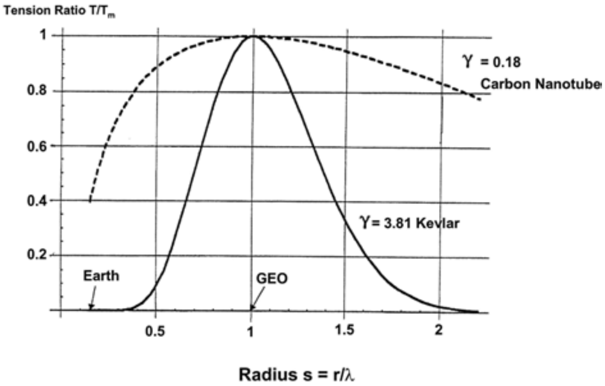

Fig. 7: Space Elevator Tether Tension vs Radius.

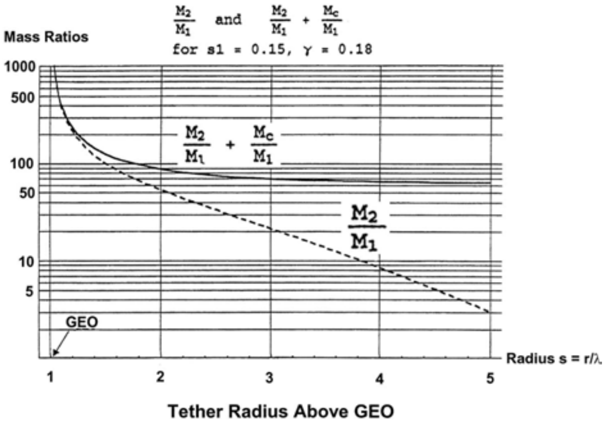

Fig. 8: Space Elevator Mass Ratio vs Radius.

Numerous other requirements need to be carefully examined, however, before the feasibility of the concept can be established. Among these are the material degradation properties in space environment, resistance to micrometeoroids and space debris, dynamics of the extremely long tethers, and the orbital perturbation effects. Once these effects have been fully assessed, the design and construction of a space elevator can be initiated leading towards a new era in space transportation and exploration.

5. SUMMARY AND CONCLUSIONS

The study examined the feasibility of designing and constructing a geosynchronous equatorial tether space debris removing system. Tether length, mass, and counterweight requirements were determined to release debris objects collected in GEO into either Earth reentry or escape type trajectories. Kevlar and the newly discovered carbon nanotube materials were considered.

The results of the study showed that an extended-length gravity-gradient-stabilized tether system in GEO could be constructed from either Kevlar or carbon nanotube materials. With a total length of 23612 km extending above and below GEO the system mass for Kevlar is on the order of 88000 kg, which includes a 10000 kg supported mass at the lower end of the tether.

A 2-mm-dia tether at GEO is reduced to 1 mm at the lower tip mass for an operational tether stress of 3.6 GPa. The total mass can be lowered significantly by either decreasing the supported lower mass or by the use of the carbon nanotube material for the tether.

The tether extension to the surface of the Earth (space elevator concept) was also considered and found to be feasible for the carbon nanotube material. The tether and counterweight mass to support a 1000 kg mass at Earth surface was found to be on the order of 90000 kg. This mass can be further reduced by a smaller support mass or a higher operational stress in the tether. The feasibility of the space elevator, however, can be established only after tether material degradation, resistance to micrometeoroids and space debris, and orbital perturbations are also assessed, including debris collection/rendezvous issues in GEO.

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References

1. Tsiolkovski, K.E. Grezy o zemle i nebe. Na Veste. Academy of Sciences of the USSR, Moscow 1959, (in Russian).
2. Artsutanov, Y., V. Kosmos na Elektrovoz, Komsomol skaya Pravda, July 31, 1960 (contents described in Lvov). Science, 1967, 158, 946.
3. Clarke, A. C., The space elevator: ‘thought experiment,’ or key to the universe. Advances in Earth Oriented Applied Science Technology, 1979, 1, 39.
4. Sutton, G.W. and Diederich, F. W., “Synchronous Rotation of a Satellite at Less than Synchronous Altitude,” AIAA Journal, Vol. 5, April 1967, pp. 813-815.
5. Chobotov, V.A., Synchronous Satellite at Less Than Synchronous Altitude, Journal of Spacecraft and Rockets, Vol 13, No. 2, February 1975, pp 126-128
6. Pearson, J., The Orbital tower: a spacecraft launcher using the Earth’s rotational energy. Acta Astronautica, 1975, 2, 785.
7. Penzo, P.A., A Low Earth Orbit Skyhook Tether Transportation System, AAS/AIAA Astrodynamics Specialist Conference, Paper No. AAS 87-436, August, 1987.

8. Edwards, B.C., Design and Deployment of a Space Elevator, Acta Astronautica, Vol 47, No. 10. pp. 735-744, 2000.
9. Chobotov, V.A., “The Space Elevator Concept as a Launching Platform for Earth and Interplanetary Missions,” ATR-2004(9368)-3, The Aerospace Corporation, El Segundo, California, 25 February 2004.
10. Beletski, V.V., Ocherky o Dvizhenii Kosmicheskih Tel, Nauka, 1977 (in Russian).
11. Cramer, J.G., “The Carbon Nanotube-Miracle Material,” Analog Science Fiction and Fact Magazine, December 2001.