Comparision between Multiple bare tethers and single bare tether for deorbiting satellites

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Abstract

This paper compares the working of multiple bare electrodynamic tethers versus a long single tethered system on a satellite in Low Earth Orbit(LEO) for end of life de-orbiting to combat the further formation of space debris. The paper demonstrates the use of several equal length short tethers, placed in parallel orientation on one face of the satellite. Tethers have proved to be efficient passive de-orbiting systems, yet tethers used in previous missions have been subjected to damage due to their extremely large lengths. The paper also upholds the fact that the same drag force can be produced using multiple tethers just like a single long tether. The calculation of de-orbiting time are presented along with the effects of initial induced voltage and current. To obtain the maximum efficiency from each short tether optimum spacing distances between the tethers are also presented.

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Symbol	**Connotation**	**Value**
B	Magnetic Field of the Earth	$2.5 \times 10^{-5} Wm^{-2}$
G	Universal Gravitational Constant	$6.673 \times 10^{-11} Nm^2kg^{-2}$
M	Mass of Earth	$6.4 \times 10^{24} kg$
v	Velocity	
ψ	Induced Voltage	
I	Current	
R_{net}	Resistance of the Tether	
ρ	Resistivity	
A	Area of Cross Section of Tether	
m_{tot}	Mass of the Satellite	
λ_d	Debye Length	
ϵ_d	Sheath Thickness	
d	Spacing Distance	
F_t	Force Produced by Tether	
m_{ion}	Mass of Ion	
m_e	Mass of Electron	$9.1 \times 10^{-31} kg$
E_{mag}	Work Done by Electromagnetic Drag Force Along the Component of Velocity	
W_t	Work Done by the Tether	
W_{grav}	Work Done Due to Gravity	

1 Introduction

Orbital debris is one of the major issues in the field of space technology, which includes uncontrollable objects in space.Any body or particle that is uncontrollable or has been left defunct constitute space debris. This includes, paints, gases, tools, and destroyed rockets and staellites. They not only pose a major threat to the existing assets in space but also affect future missions too. According to the National Space Society (NSS), there are about 22,000 Earth-orbiting debris pieces that are larger than 10cm size, around 7,00,000 fragments between 1cm and 10cm range, and the number of tiny bits that are smaller than 1cm exceeds 100 million [3].

Orbital debris persist in space due to the lack of on-board de-orbiting mechanisms that could dispose of the satellite at the end of the mission. These abandoned satellite have no control over their trajectories and hence can lead to collisions resulting in the generation of more debris. Inter-Agency Space Debris Coordination Committee (IADC) has made guidelines that any object put into Low Earth Orbit (LEO) should not have an orbital lifetime for more than 25 years post the end of its useful life [4]. Hence several institutions and organizations have proposed and tested different de-orbiting mechanisms[5].

de-orbiting mechanisms can be of two types, active and passive. Passive de-orbiting mechanisms do not require a power supply from the spacecraft, need no monitoring, and also can perform re-entry more effectively. Among passive de-orbiting mechanisms, electrodynamic tethers (EDT) are one of the most effective systems. This study focuses on the physics behind electrodynamic tethers, while addressing a possible solution for optimization of it's length. The length of single tethers is proposed to be reduced by replacing it with a set of multiple short tethers, without affecting much of its intended performance.

2 Methodologies and Theory

2.1 Premise

For the purpose of this study, the magnetic field of the Earth is considered to be constant along the orbit and altitude of consideration. The variation of solar irradiance is ignored as the satellite is within the bounds of Van Allen belt. The orbits are considered to be equatorial and circular in LEO. The oblateness of the Earth is ignored. The ambient plasma condition in the ionosphere is considered to be quasi-neutral. Only prograde satellites are being considered. The study considers microsatellite of a mass of 100kg. If found effective, this mechanism of multiple tethers can be implemented for various classes of satellites. The study looks into the performance of the tether system in orbit, and does not consider the structural properties of the system.

2.2 Basics of Electrodynamic Tether

EDT works on the principle of electro-motive force the presence of the magnetic field of the Earth induces a current in the conductor (the tether), that moves relative to it. The motion of the satellite is from west to east i.e., eastward. The tether is deployed from the satellite in the direction radially towards the Earth. When a conductor is moved in a magnetic field with some relative velocity such that it cuts the field lines, voltage is induced in the conductor as a consequence. The induced voltage in the tether (ψ) can be obtained from the cross product of the velocity of the tether (v) and the magnetic field (B) where the direction will be radially away from the Earth as given by the below equation:

$$(\psi) = \int_0^L (v \times B) d\mathrm{l} = vBL \sin\theta,$$

where L is the length of the tether and θ is the angle between the direction of velocity and direction of the magnetic field.

Hence the current (I) induced due to the induced voltage(ψ) will also be in the direction away from the Earth given by

$$I = \frac{\psi}{R_{net}} = \frac{vBL}{R_{net}},$$

where R_{net} is the resistance of the tether.

The Lorentz force (F_t) produced by the induced current (I) is given by the below expression where its direction will be opposite to that of the velocity of the satellite and thus help in reducing the orbit altitude gradually.

$$F_t = \int_0^L (I \times B) d\mathrm{l} = BIL \sin\alpha,$$

where α is the angle between the direction of current and magnetic field.

In this method the EDT can be used to de-orbit a satellite from the orbit. The induced voltage produces a current in the tethers, a complete path of current is formed in the ambient plasma with help of contactors, which act as electron flow medium between the tethers and the ambient plasma. This current in the tether is responsible for producing the required force, the drag force, for de-orbiting.

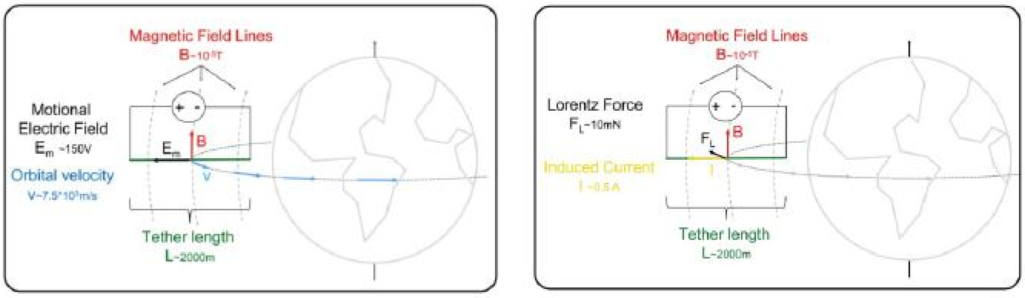


Figure 1: Electrodynamic tether and lorentz force[1]

2.3 Debye Length

Debye length is the measure of the net electrostatic effect of charge carriers in a solution and how far its electrostatic effect persists. Debye length is denoted by λ_d, it can be defined as the decrease in the magnitude of the electric field by a factor of 1/e, where e is the charge of the electron.

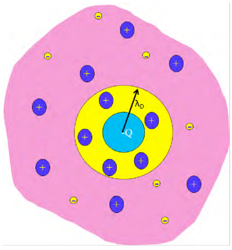


Figure 2: A tether(blue) placed in plasma(pink) having Debye length (λ_d)[2]

2.4 Orbital Motion Limited Theory

According to Orbital Motion Limited (OML) theory[6], the orbital-motion-limit regime is attained when the cylinder radius is small enough such that all incoming particle trajectories that are collected are terminated on the cylinder's surface while being connected to the background plasma. In an electrodynamic tether system and for a given mass of tether, the best performance is achieved for a tether diameter chosen to be smaller than 1 electron Debye length, for typical ionospheric ambient conditions from 200 to 2000 km altitude range.[7]

2.5 Effect of Quasi Neutral Plasma on Conductors

Consider a plasma which has an equal number of electrons and ions. Let a conducting metal wire be placed inside the plasma. It is observed that a sheath gets formed around this conducting surface. The sheath arises because of the following reasons. The electrons usually have a temperature of the order equal to or greater than that of the ions, and electrons are comparatively very light than ions. Speed of electrons is greater than speed of ions by a factor of $\sqrt{\frac{m_{ion}}{m_e}}$, where m_{ion} is the mass of ion and m_e is the mass of electron.
As the plasma is considered as neutral plasma, with the assumption that the number of electrons and the number of ions in the plasma is about 100, due to the high speed of the electrons for every 1 ion collision with the surface of the conductor, there would have been 100 electrons that would have collided with the surface. Due to this movement of electrons and ions, the surface of the tether gets negatively charged and due to the electrostatic force of attraction, positive ions get accumulate around the metal surface to balance the negative charge on the surface. This layer is called the Debye sheath.

2.6 Debye Sheath

Debye sheath is a layer in plasma which has a greater density of positive ions, and hence an overall excess positive charge, that balances an opposite negative charge on the surface of a material with which it is in contact. The thickness of this layer can be several "Debye length" thick, a value whose size depends on various characteristics of plasma, like temperature, density, etc.[8] This formula gives the sheath thickness in terms of Debye length.

$$\epsilon_d = \frac{d}{\lambda_d} = (\frac{1}{c_1} \ln [\sqrt{\frac{m_{ion}}{2\pi m_e}}])^{3/4} \tag{1}$$

where d is the sheath thickness.

3 Design and Analysis

3.1 Force for Constant Current

Consider a tether of length L and let voltage induced by this tether be

$$\psi = \int_0^L (v \times B) d\mathrm{l},$$

where v is the velocity of the satellite and B is the magnetic field of earth. By integrating, the following equation is obtained,

$$\psi = vBL,$$

where L is the length of a single tether. Now consider a short tether of length L/N, keeping the material and the area same.
The induced voltage is

$$\psi' = \int_0^{L/N} (v \times B) d\mathrm{l},$$

$$\psi' = \frac{vBL}{N},$$

$$\psi' = \frac{\psi}{N}. \tag{2}$$

So the length of the tether affects the voltage induced by the tether.

3.1.1 Force by a Long Tether

The force acting on the tether is

$$F_t = \int_0^L (I \times B) d\mathrm{s},$$

which, when integrated gives,

$$F_t = BILsin(\theta),$$

where θ is the angle between direction of current I and magnetic field B. The tether is placed perpendicular to the direction of magnetic field of Earth, therefore $\theta = 90^\circ$ and voltage is given by

$$\psi = IR_{net},$$

where R_{net} is the net resistance of the tether.

$$I = \frac{\psi}{R_{net}},$$

And

$$R_{net} = \frac{\rho L}{A},$$

where ρ is the resistivity of the tether and A is the cross sectional area of tether.
Therefore force produced by the tether is

$$F_t = \frac{B\psi L}{\frac{\rho L}{A}},$$

$$F_t = \frac{B\psi A}{\rho}. \tag{3}$$

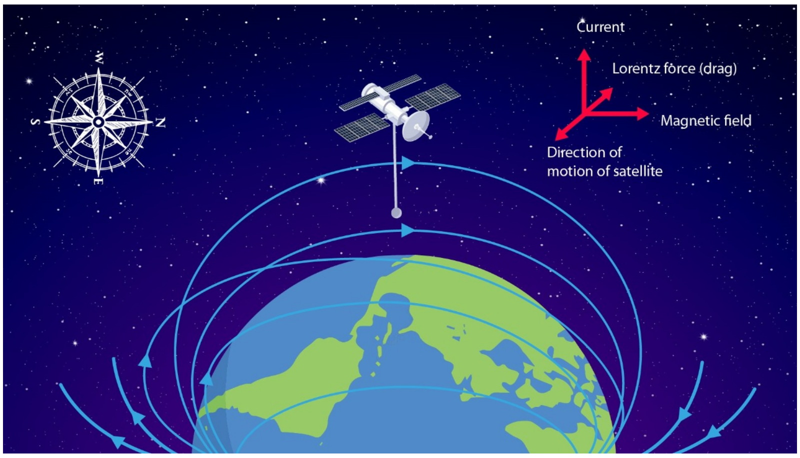


Figure 3: Force on a single long tether

3.1.2 Force by a Short Tether

Since the tethers are placed parallel to each other and the force is in the same direction, the force for a shorter tether of length L/N is,

$$F_i = \int_0^{L/N} (I \times B) ds,$$

where I is current and B is magnetic field.
Now by integrating,

$$F_i = \frac{B\psi' A}{N\rho},$$

$$F_i = \frac{F_t}{N}. \tag{4}$$

As the induced voltage reduces due to reduce in length, the force also reduces.
But when there are N such short tethers, the force is same as that due to single long tether

$$F_{tm} = F_t. \tag{5}$$

Therefore the force produced by a single tether is equal to the force produed by multiple tethers whose lengths sums up to the length of the single tether.

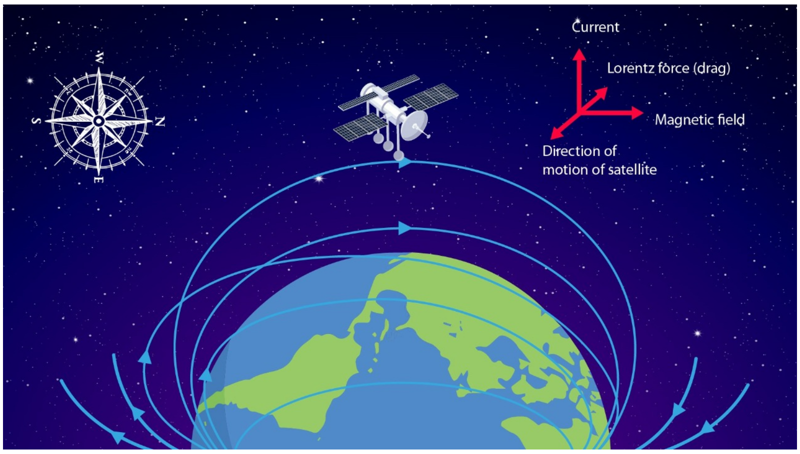


Figure 4: Force on multiple short tethers

3.2 Force due to Changing Current

The previous section derived the force for a constant current condition. But since the current changes throughout the process of de-orbiting, so will the force. Hence, the force produced is modelled as follows.

3.2.1 Force on a Single Tether due to Changing Current

By lorentz force,

$$F_t = BI(t)L,$$

$$\frac{dF_t}{dt} = BL\frac{dI}{\mathrm{dt}}, \tag{6}$$

$$\frac{dI}{\mathrm{dt}} = \frac{d\psi}{\mathrm{dt}}\frac{1}{R_{net}}. \tag{7}$$

By Faraday's law of electromagnetic induction, induced voltage is given by,

$$\frac{d\psi}{\mathrm{dt}} = LB\frac{d\mathrm{v}}{\mathrm{dt}}. \tag{8}$$

By Newton's second law of motion,

$$\frac{d\mathrm{v}}{\mathrm{dt}} = -\frac{F_t}{m_{tot}}. \tag{9}$$

From 6 7, 8 and 9

$$\frac{dF_t}{\mathrm{dt}} = -\frac{B^2L^2F_t}{m_{tot}R_{net}}.$$

Transposing the terms

$$\frac{dF_t}{F_t} = -\frac{B^2L^2dt}{m_{tot}R_{net}}.$$

Integrating on both sides from $t_0 = 0$ to t and force $F_t = F_0$ when $t_0 = 0$

$$\ln\frac{F_t}{F_0} = -\frac{B^2Lt}{m_{tot}R_{net}},$$

$$\frac{F_t}{F_0} = e^{\frac{-B^2L^2t}{m_{tot}R_{net}}}. \tag{10}$$

At $t = t_0$, $F_t = F_0$ and $I = I_0$, hence,

$$F_0 = BI_0L,$$

and $I_0 = \frac{\psi_0}{R_{net}}$,

$$I_0 = \frac{v_0BL}{R_{net}},$$

$$v_0 = \sqrt{\frac{GM}{r_0}},$$

$$I_0 = \frac{BL}{R_{net}}\sqrt{\frac{GM}{r_0}},$$

Therefore 10 becomes,

$$F_t = \frac{B^2L^2}{R_{net}}\sqrt{\frac{GM}{r_0}}e^{\frac{-B^2L^2t}{m_{tot}R_{net}}} \tag{11}$$

This is the force produced by a single tether of length N due to changing current.

3.2.2 Force on Multiple Tethers due to Changing Current

By lorentz force,

$$F_i = \frac{BI_iL}{N},$$

where F_i is the lorentz force and I_i is the current in a single short tether.

$$\frac{dF_i}{dt} = B\frac{L}{N}\frac{dI_i}{dt}. \tag{12}$$

$$\frac{dI_i}{dt} = \frac{d\psi_i}{dt}\frac{N}{R_{net}}. \tag{13}$$

$$\frac{d\psi_i}{dt} = \frac{BL}{N}\frac{dv_N}{dt}. \tag{14}$$

$$\frac{dv_N}{dt} = -\frac{F_{tm}}{m_{tot}} = -\frac{NF_i}{m_{tot}}. \tag{15}$$

where F_{tm} is the force by multiple tethers.
From 12,13,14 and 15

$$\frac{dF_i}{dt} = -\frac{B^2L^2F_i}{m_{tot}R_{net}}. \tag{16}$$

By transposing the terms,

$$\frac{dF_i}{F_i} = -kdt$$

Where $k = \frac{B^2L^2}{m_{tot}R_{net}}$.
Integrating both sides from F_{i0} to F_i and t is from 0 to t

$$\ln\frac{F_i}{F_{i0}} = -kt,$$

$$F_i = F_{i0}e^{-kt},$$

$$F_{i0} = \frac{BLI_{i0}}{N},$$

$$I_{i0} = \frac{v_0 B\frac{L}{N}}{\frac{R_{net}}{N}},$$

$$F_{i0} = \frac{B^2L^2v_0}{NR_{net}} = \frac{F_0}{N}.$$

Therefore,

$$F_{tm} = \frac{F_0e^{-kt}}{N}N.$$

But there are N such tethers and their individual forces act on the same satellite in the same direction. Therefore,

$$F_{tm} = F_t. \tag{17}$$

Thus all calculations henceforth will have the bearing for both single tethered system as well as multiple tethered system. Which implies that the de-orbiting time by single tether and multiple tether are the same.

3.3 Distance between Adjacent Tethers

Consider a condition where two conductors are placed in the plasma in proximity of each other, a positive ion sheath is formed over the conductors. When the spacing between the two conductors is less than the minimum required spacing, the net positive ions around each conductor reduces as there will be interference with the sheath of adjacent conductors. This results in the distribution of positive charges between the interfering sheaths. The reduction of positive ions in the sheath will in return reduce the number of electrons on the sheath-contact surface of the conductor resulting in the reduction of the current in the individual conductor. Hence, if each of the tethers is placed outside the sheath radius of its adjacent tether, there will not be any reduction of induced current. Maintaining a minimum spacing of twice the sheath radius of the individual tether will prevent any loss of performance, as there will be no interference between the sheath of adjacent tethers. The following table is one such example.
Here oxygen ions have been taken where its mass is

$$m_{ion} = 16.022 \times 10^{23},$$

The constant

$$C_1 = 1.36.$$

Thus from 1,

$$d = 3.39\lambda_d.$$

Altitude (km)	$4\lambda_d(mm)$	Sheath thickness d(mm)	Spacing distance
650	7.25	24.57	49.14
700	8.25	27.967	55.93
750	8.5	28.815	57.63
800	8.5	28.815	57.63
850	9.75	33.052	66.104
900	12.25	41.527	83.054
950	13.75	46.612	93.224
1000	16	54.24	108.48

Table 1: Table relating Debye length, sheath radius and spacing distance with different altitudes (The first 2 columns of the table are from effects of electron emission on plasma sheaths [8])

3.4 De-orbiting Time due to Changing Current

By lorentz force,

$$\frac{dF_t}{dt} = BL\frac{dI}{dt}, \tag{18}$$

$$\frac{dI}{dt} = \frac{d\psi}{dt}\frac{1}{R_{net}}. \tag{19}$$

By Faraday's law of electromagnetic induction, induced voltage is,

$$\frac{d\psi}{dt} = LB\frac{dv}{dt}. \tag{20}$$

By Newton's second law of motion,

$$\frac{dv}{dt} = -\frac{F_t}{m_{tot}}. \tag{21}$$

From 18, 19, 20 and 21

$$\frac{dF_t}{dt} = -\frac{B^2L^2F_t}{m_{tot}R_{net}}.$$

By transposing terms,

$$\frac{dF_t}{F_t} = -\frac{B^2L^2dt}{m_{tot}R_{net}}.$$

Integrating on both sides from $t_0 = 0$ to t and force $F_t = F_0$ when $t = t_0$

$$\ln F_t - \ln F_0 = -\frac{B^2L^2(t-t_0)}{m_{tot}R_{net}},$$

$$F_t = F_0e^{-kt}$$

where $k = \frac{B^2L^2}{m_{tot}R_{net}}$.

$$F_0 = BLI_0,$$

$$I_0 = \frac{\psi_0}{R_{net}},$$

$$\psi_0 = v_0BL,$$

$$F_0 = \frac{B^2L^2v_0}{R_{net}},$$

$$v_t = v_0 + \frac{F_0e^{-kt}}{km_{tot}} - \frac{F_0}{km_{tot}}.$$

As $F_0 = kv_0m_{tot}$,

$$r_t = r_0 - \frac{F_t}{k^2m_{tot}},$$

$$\frac{dE_{mag}}{dt} = F_tv_t + \frac{dF_t}{dt}\int v_tdt.$$

$$Power = \frac{F_t^2}{km_{tot}} - kF_tr_0 + \frac{F_t^2}{km_{tot}}.$$

Integrating on both sides from $t_0 = 0$ to t, so F from F_0 to F_t and r from r_0 to r_t

$$W_t = -F_tr_0 - \frac{F_t^2}{k^2m_{tot}} + F_0r_0 + \frac{F_0^2}{k^2m_{tot}},$$

$$W_t = F_0r_0(1-e^{-kt}) + \frac{F_0^2}{k^2m_{tot}}(1-e^{-2kt}).$$

By substituting $F_0 = kv_0m_{tot}$,

$$W_t = kv_0m_{tot}r_0(1-e^{-kt}) + \frac{k^2v_0^2m_{tot}^2}{k^2m_{tot}}(1-e^{-2kt}),$$

$$W_t = kv_0m_{tot}r_0(1-e^{-kt}) + \frac{k^2v_0^2m_{tot}^2}{k^2m_{tot}}(1-e^{-2kt}),$$

$$W_t = v_0^2m_{tot}[\frac{kr_0}{v_0}(1-e{-}kt) + (1-e^{-2kt})]. \tag{22}$$

$$W_{grav} = (\frac{GMm_{tot}}{r_t^2} - \frac{m_{tot}v_t^2}{r_t})r_t - (\frac{GMm_{tot}}{r_0^2} + \frac{m_{tot}v_0^2}{r_0})r_0,$$

$$W_{grav} = \frac{GMm_{tot}}{r_t} - m_{tot}v_t^2 - \frac{GMm_{tot}}{r_0} + m_{tot}v_0^2.$$

Orbital velocity at an orbit orbit of radius r_0 is $v_0 = \sqrt{\frac{GM}{r_0}}$,

$$W_{grav} = \frac{GMm_{tot}}{r_t} - m_{tot}v_t^2,$$

$$W_{grav} = v_0^2 m_{tot}[\frac{r_0}{r_t} - 1]. \tag{23}$$

$$W_t = W_{grav},$$

$$\frac{r_0}{r_t} - 1 = \frac{kr_0}{v_0}(1 - e^{-kt}) + 1 - e^{-2kt}. \tag{24}$$

By solving this equation using the above mentioned software some inferences were derived which are explained in the next section.

4 Results and Conclusions

Graphs were plotted for the following sample data for three separate objects.

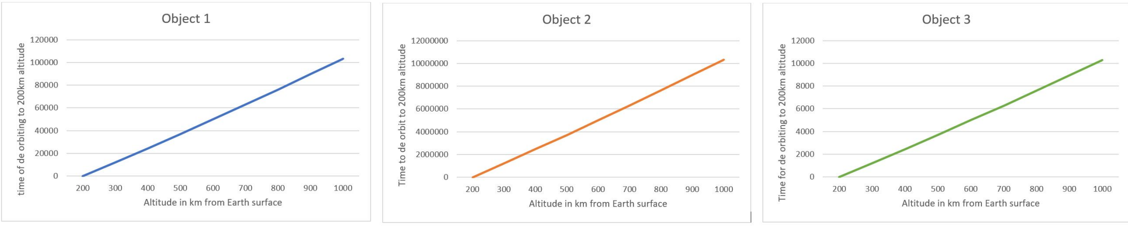
Object	Mass (in kg)	Length (in km)	Total resistance of tether(in kΩ)
Object 1	100	10	1
Object 2	100	1	1
Object 3	10	10	1

It can be observed that the de-orbiting time, as a result of the force produced by the tethers, decreases, from higher altitudes to 200km above the Earth's surface.
It can also be observed that the multiple tethers does not affect the de-orbiting time as the total force produced multiple tethers, F_t, is same as that of a single tether and even the velocity v_t expression remains the same.
The Energy is only dependent on the above mentioned variables and other common arbitrary and pre-specified constants r_o, m_{tot}, etc. which are taken to be equal for comparison purposes owing to same initial conditions.

Altitude in km	Object-1 time (in s)	Object-2 time (in s)	Object-3 time (in s)
200	0	0	0
300	12210	1221000	1218
400	24610	2462000	2455
500	37210	3722000	3711
600	50000	5001600	4986
700	63000	6302500	6283
800	76220	7624800	7600
900	89660	8969400	8939
1000	103300	10337000	10300

Table 2: Table relating the time that each object would take to de-orbit from its own orbit to 200km altitude, for given characteristics.

Notice that as the Keplerian orbit being considered from 200km altitude initially, yields 0 de-orbiting time, as it is already there at the required resultant position.
The de-orbiting time was calculated by plotting the total energy expression on Desmos (`https://www.desmos.com/calculator`), an online graphing calculator, against the X axis of time, and finding the root of the constraint, which would give us the de-orbiting time when the net condition of W_t and W_{grav} would be equal, their difference being 0. Thus, the value of the X intercept by the function of total work-energy, yields us the solution required.



(a) Object 1 (b) Object 2 (c) Object 3

Figure 5: Time of de-orbiting versus altitude

From the graphs, we can see that the nature of variation of de-orbiting time with initial altitude is similar in nature to that of the other objects.

5 Future Scope

From past papers and by observing the properties of multiple conductors in quasi-neutral plasma, this paper uses the Child Langmuir equation to calculate the thickness of the sheath around multiple tethers and has theoretically proposed the concept of optimum distance between two tethers. Experimental results need to verify this proposal and conclude the optimum distance between the tethers. The sheath to sheath interactions is also open for experimental verification, which can provide greater insight into the behavior of plasma itself. A setup can be demonstrated to develop and verify short multiple tethers, whose length sums up to be equal to the length of a single long tether can produce the same force can also be verified. Apart from the experimental analysis of the deployment mechanics required for multiple tethers, the circuitry of the contactors can begin the era of multiple tethers for future de-orbiting mechanism. This paper extensively works with the consideration of microsatellites for analysis, if efficient enough multiple tethers can be modulated to all classes of satellites.

6 Summary

The paper provides an introductory analysis of the concept of using multiple tethers rather than a single long tether to produce the required drag force to de-orbit a satellite.
The paper also introduces the concept of optimum distance between the tethers so as to avoid any interactions between the plasma sheaths of the multiple tethers. It is essential that the multiple tethers need to placed at appropriate distances to produce the same electrodynamic drag forces as a long tether to de-orbit the satellite within the same de-orbiting time with a single large tether. The plasma sheath to sheath interactions, though, having not much available literature, has been excluded from consideration.

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