Predicting Tether Performance Under Different Space Weather Conditions: A Guide for Mission Planning and Design Decisions

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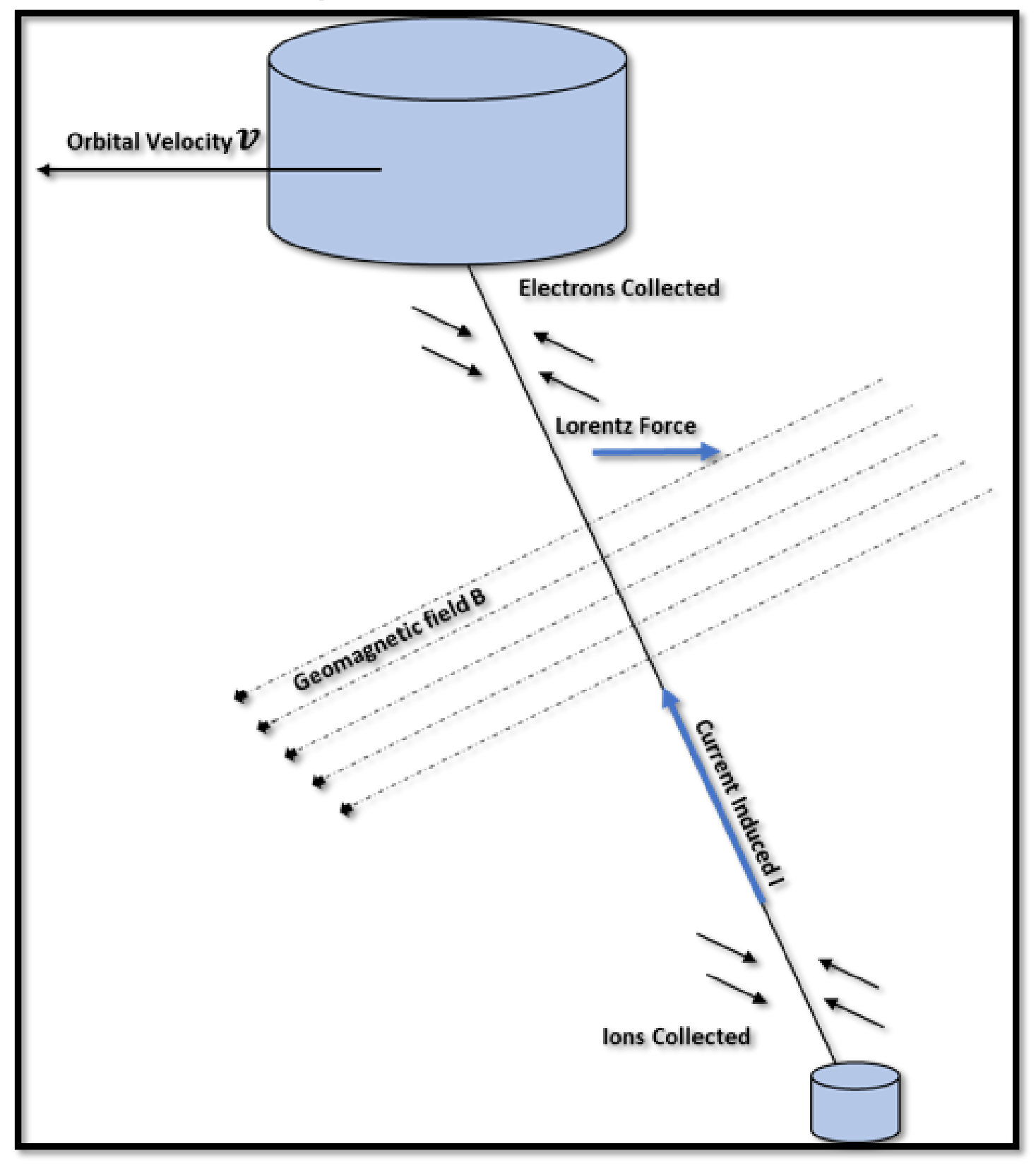
1. Abstract

Electrodynamic tethers have demonstrated to be effective for fuel-free de-orbiting or station-keeping for spacecraft in Low Earth Orbit. However, the effect of solar activity on the plasma environment around the tether is still an underestimated factor that can have a significant impact on the efficiency and viability of such systems. This study aims to enhance the understanding of tether system design by investigating the influence of solar conditions and space weather on critical parameters such as tether length and power requirements across different spacecraft sizes. The performance of tethers in space is significantly influenced by various environmental factors, including space weather phenomena such as Spread-F, geomagnetic storms, and ionospheric disturbances. The research assesses solar conditions encompassing Solar Maxima (F10.cm at 115), Solar Minima (F10.7cm at 69), and the 2015 solar storm (F10.cm at 250). Variations in solar activity caused changes in aerodynamic drag, impacting both tether design factors for its utility in de-orbiting and station-keeping. Elevated drag during periods of heightened solar activity needs increased thrust for station-keeping, resulting in bigger tether length and power consumption. Additionally, higher drag requires shorter tether lengths to achieve similar de-orbiting performance. These findings have important possibilities for mission planning and spacecraft design decisions, including the optimal tether length and power requirement.

2. How Electrodynamic Tether works

The motion of an Electrodynamic tether in the highly conductive plasma surrounding the tether (meters away, typically) where the electric field is negligible, creates an external motional electric field E_m. The E_m field can drive a current in a tether deployed in the vertically downward direction normally aligned with the direction of gravity, pointing towards the center of the planet or celestial body [reference]



- Electromotive Field induced as a result of the tether motion in Earth's magnetic field

$$EMF = \int (\bar{v}\ x\ \bar{B})\overline{dl}$$

- The maximum electron current generated in the tether as defined by the OML Equation

$$I_{OML} = 4\pi r L e N_{\infty} \mathrm{x} \sqrt{\frac{2e\phi_p}{\pi m_e}}$$

- The Lorentz force generated in the opposite direction to the Tether Current which is used to create Drag or Thrust

$$F_E = \mathrm{L\ x\ (I\ x\ B\ )} = \frac{-L^2 B_T^2 v_o cos\propto}{R_{tether}}$$

Fig1: Electrodynamic Tether operation in Drag mode

Where,

F_E = Lorentz Force,
L = length of the tether,
I = current Induced,
B = magnetic field strength,
R_{tether} = radius of the cylindrical tether,
v = velocity of the spacecraft, and
cos α = angle between the tether and the geomagnetic field

The simplest method to determine the current produced in a tether was developed by Sanmartin and Estes which till date remains the most widely used formula [1]. The Orbital Motion Limited (OML) theory is extensively used as the basis of the charge collection of bare EDTs [2]. The tether is assumed to be of cylindrical geometrical features placed in a non-flowing, collisionless, unmagnetized plasma.

The radius of a tether collecting OML current in an unmagnetized plasma at rest cannot exceed values higher than the Debye length.

$$R_{max} >> \lambda_{De}$$

R_{max} = Maximum radius of the tether
λ_{De} = Debye Length

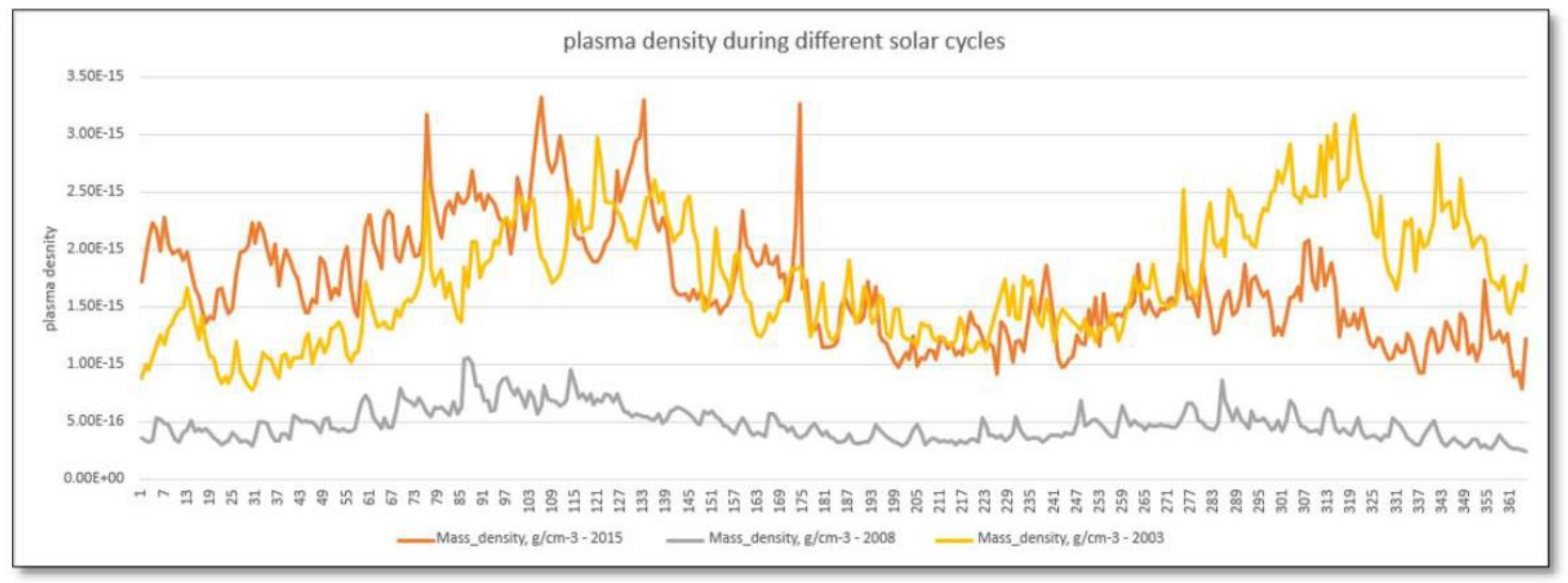
3. Solar activity impact on operating environment

Spacecraft operations have traditionally been carried out in Low Earth Orbit (LEO) (>450km), but there is a growing interest in exploring Very Low Earth Orbit (VLEO) (<450km) for future space missions. In LEO and VLEO orbits, aerodynamic drag leads to altitude loss over time and results in lower orbital lifetimes. The drag experienced calculated by eq (1) depends on the plasma density, spacecraft velocity and spacecraft surface area.

$$F_{drag} = \frac{1}{2} C_D A_s \rho v^2 \qquad \text{Eq (1)}$$

The aerodynamic density varies with altitudes and solar activity, which in turn affects the design of the tether system and the required power for de-orbiting and station-keeping applications. The plasma density in the ionosphere undergoes variations due to solar activity, resulting in the expansion and contraction of the ionosphere. Higher solar activity leads to increased drag on spacecraft orbiting in VLEO and LEO. The solar index F10.7cm is considered an approximation of solar activity. Figure (2) illustrates plasma density values for solar minima, solar maxima, and a year with an intense geomagnetic storm (2015).

Fig2: Atmospheric plasma density at 500 Km altitude at different solar cycles



During periods of high solar activity or geomagnetic storms, the ionosphere's density can increase up to 117%, which can cause mission failures or excessive debris creation due to faster de-orbiting.

Fig3: Aerodynamic drag induced on a 6U CubeSat at 500 Km altitude

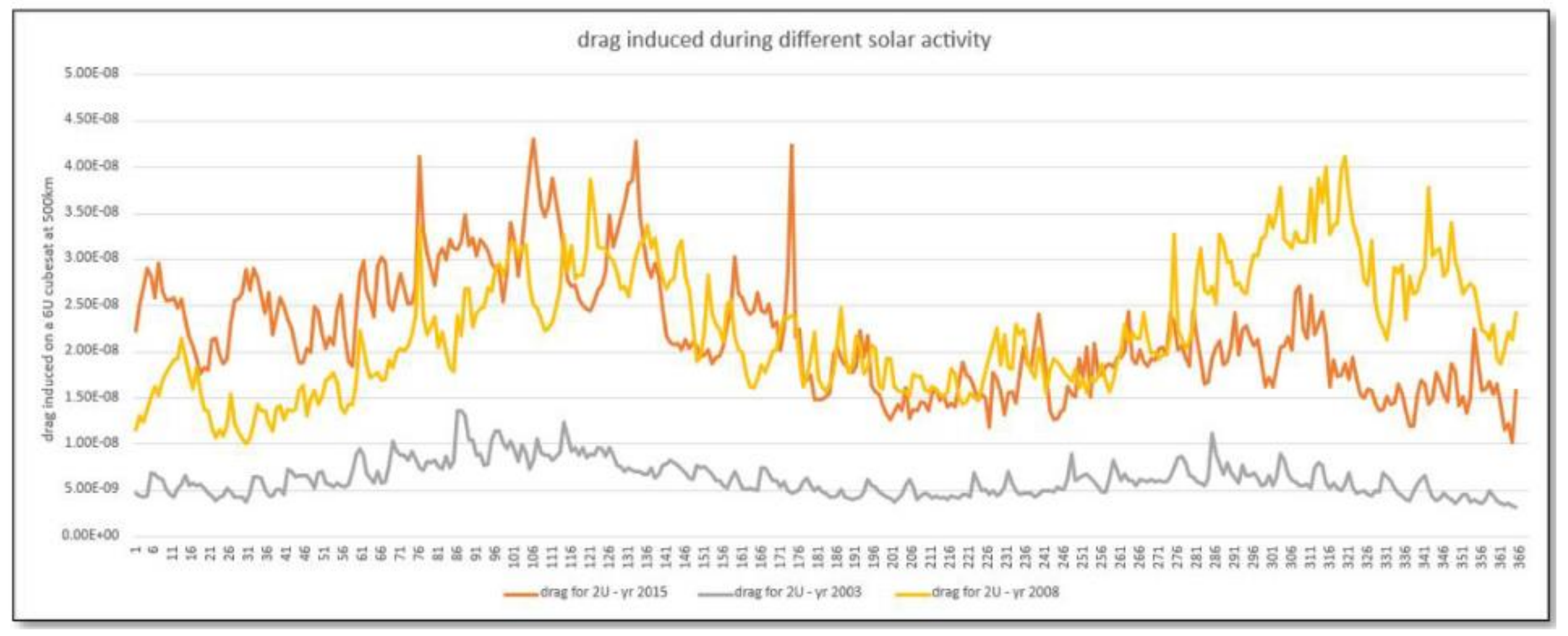


Figure (3) uses the calculated drag on a 6U CubeSat, which changes with plasma density, to show how drag varies with varying degrees of solar activity. Since various propulsion levels would require different tether lengths and Power requirements for the system, solar weather conditions of the spacecraft lifespan must be taken into consideration while developing the tether system. Efficient design considerations will improve tether performance design and tether system viability decision-making.

The Different payload sizes considered to study the variation in the tether system design characteristics are shown in Table 1

Table1: Payload sizes considered

Spacecraft Dimensions	Surface Area m^2
IU Cubesat 10cm x 10cm x 10cm	0.03
35.9 kg payload 0.7m x 0.64m x 0.54m	1.17
300 kg payload 1.5m x 1.95m	10.8

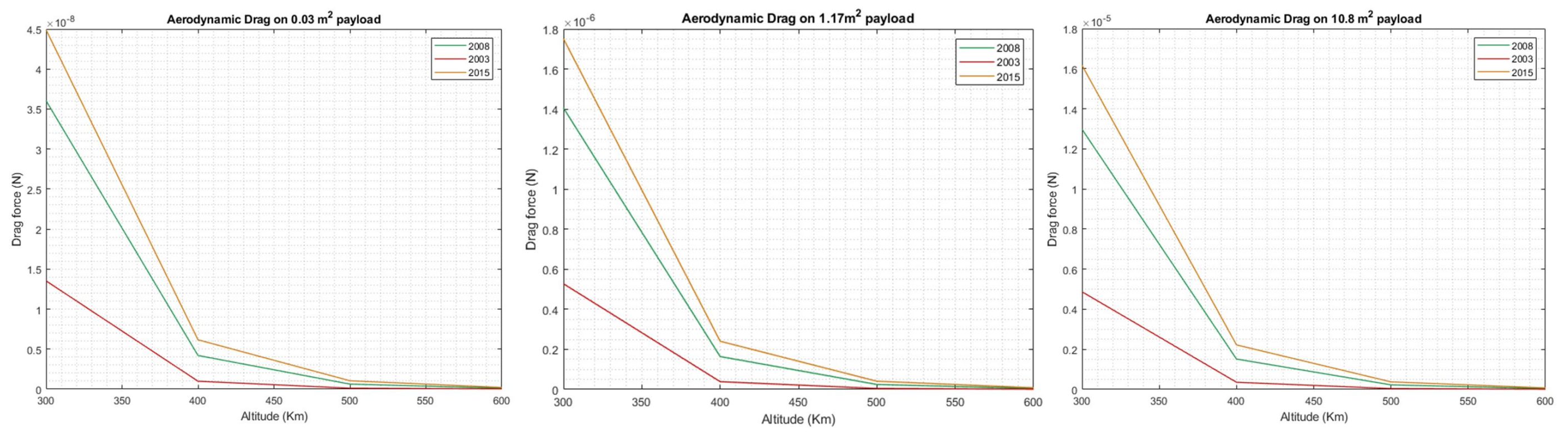
The spacecraft sizes are considered to show the different spacecrafts in LEO and define the impact on the tether system for each spacecraft size.

4. Tether Length and Power Requirements

For the calculation of the tether performance and the power requirement in different solar conditions, three phases of the solar cycle as discussed in the sections above have been taken. The instantaneous value of the space weather index F10.7cm is considered for solar minima, solar maxima, and a geomagnetic storm in 2015. This study investigates the relationship between spacecraft size, solar activity (solar maxima and solar minima), tether length required to overcome drag, and the corresponding power requirements.

Different spacecraft sizes experience varying drag forces due to their cross-sectional area and mass. The drag induced on each payload size considered is shown in Figure 4, where the change the drag variation for different solar cycles is calculated:

Fig4 : Aerodynamic drag variation due to solar activity on different spacecraft sizes at different altitudes.



With the different solar activity, the drag that acts on the spacecraft is higher for the altitudes as low as 300km. Spacecrafts in VLEO orbits (< 450km) experience the higher drag and as we the altitude increase the mass density decreases reducing the drag on the spacecraft. Higher drag facilities the de-orbiting of a spacecraft resulting in lower re-entry time whereas higher power is required to used EDTs for station keeping. Fig 5 shows how the tether length changes for the thrust needed in different solar conditions. Higher tether length, impact deployment systems, tether dynamics as well as tether cut probability.

Fig5: Thrust generated for the required tether length in different solar activity.

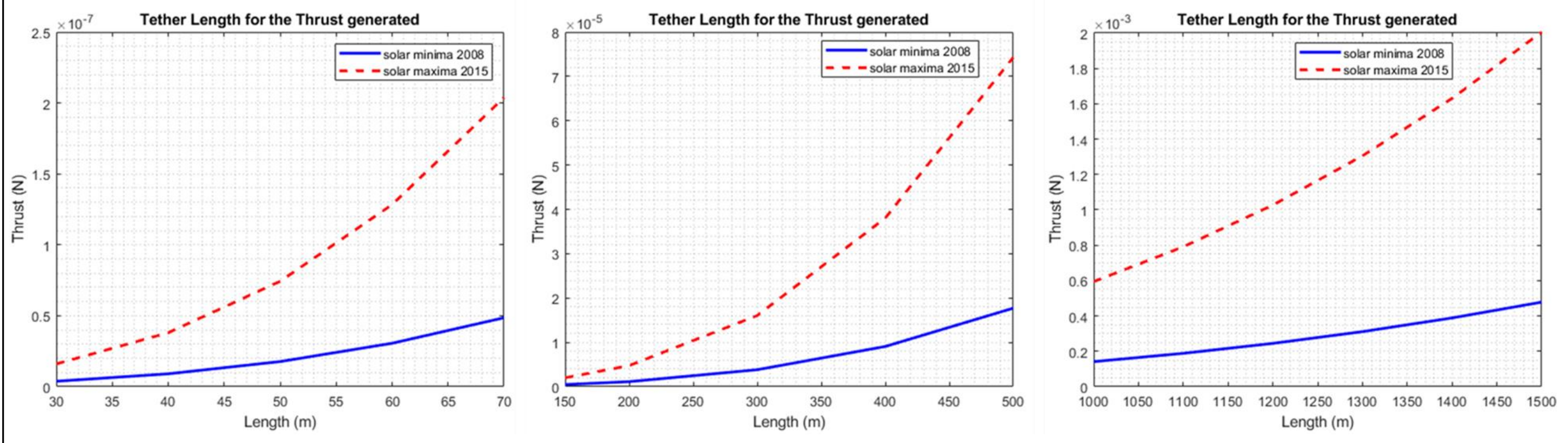
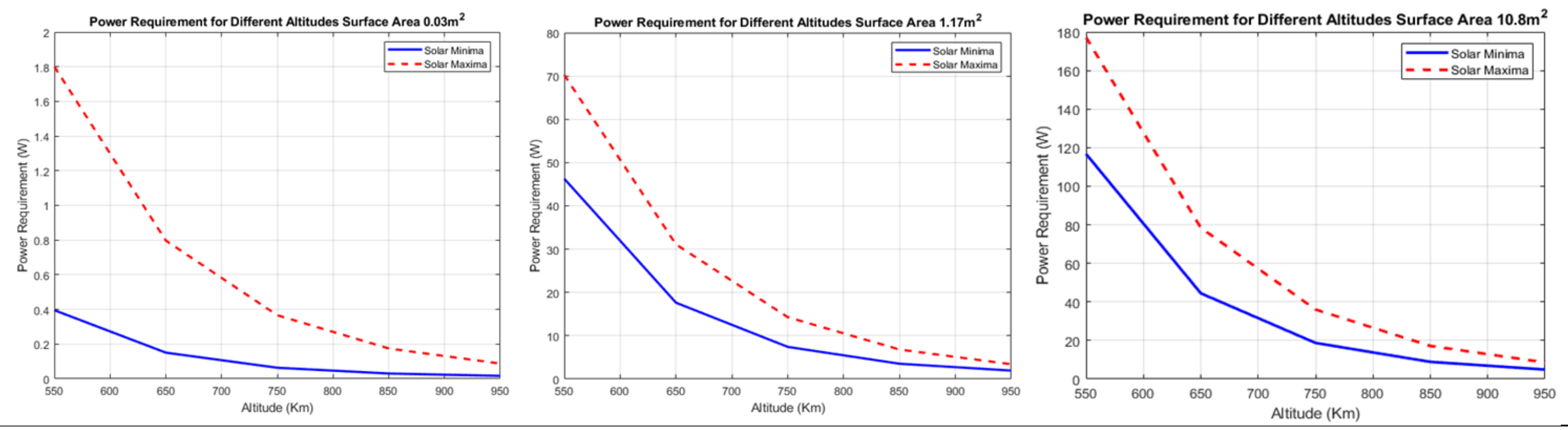


Fig 6 shows how the power requirement for different spacecraft sizes and the solar activity. The power required to generate Thrust to overcome the drag at different altitude will have a substantial impact of the tether system design. Longer tether lengths and power requirement impact the tether mass to satellite mass ratio which is used to measure tether performance and is an important factor in tether design.

Fig6: Power required for Operating EDT system for different solar activity



5. Conclusion

This paper provided insights into EDT systems under varying solar conditions, emphasizing their role in station-keeping propulsion. Solar activity significantly influences tether design, affecting optimal lengths for drag compensation. Higher solar activity requires longer tethers, while lower activity permits shorter yet effective tethers. Solar conditions also impact power requirements for thrust generation. High activity demands more power to counteract intensified drag, while low activity reduces power consumption. Recognizing solar effects is crucial for efficient power management, tether sizing, and reliable station-keeping.

The tether sizing and power requirements for efficient operation will impact the tether deployment mechanisms as well tether performance in terms of tether cut probability, Tether system mass efficiency and Tether efficiency to operate in the available power.

6. Future Work

In this study only solar activity is taken as a factor for the tether system design characteristics. Through Tether length and Required Power are important other variable also need to be considered for efficient EDT system operation.

Other Variables that will be considered for future work :

Tether Diameter and Shape: The cross-sectional diameter and shape of the tether can influence the distribution of current along its length. Investigate how variations in tether geometry impact current collection, power distribution, and electrodynamic effects.

Tether Material: The choice of tether material and its surface properties can affect current collection efficiency and overall system performance.

Space Weather and Radiation: Examine the influence of space weather events, such as solar flares and geomagnetic storms, on tether performance. Understand how radiation exposure may impact tether conductivity and thrust generated.

Space Debris: Study the effects of space debris, micrometeoroids, and contaminants on the tether system survivability.

The tether system feasibility for different applications and operating environments is needed to improve our understanding of tether operations and efficient system design guidelines. Evaluating the potential power consumption, improved mission efficiency, and extended operational lifetimes will guide mission planners and decision-makers.

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