Dynamics and Control of Spinning ElectroDynamic Tethers Applied to Space Sustainability

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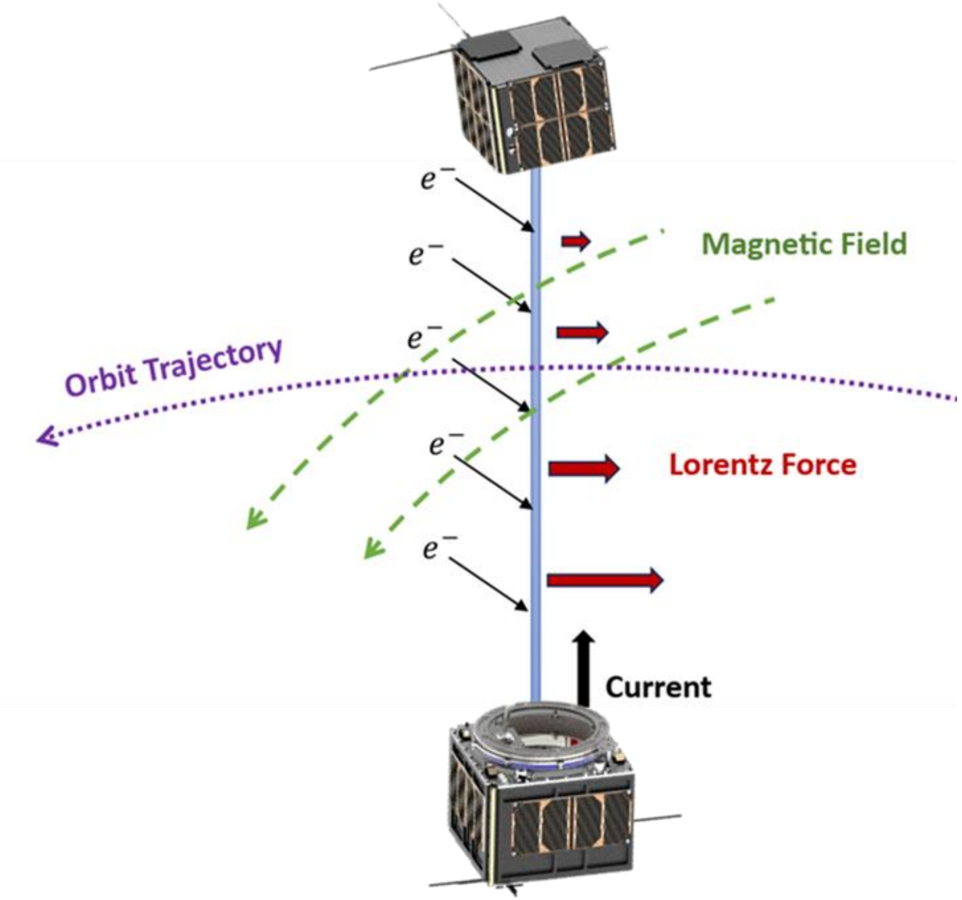
Introduction

- ElectroDynamic Tethers (EDTs) are long, orbiting conductors used for diverse aerospace applications, such as propellant-less propulsion for deorbiting, re-boosting, station keeping, among others
- As the tether moves at a velocity $\boldsymbol{v}$ through a conducting plasma and a magnetic field $\boldsymbol{B}$, an electric current I may be induced along its length
- Lorentz force appears due to the interaction of the geomagnetic field $\boldsymbol{B}$ with the electric current I
- When placed along the local vertical (nadir pointing), a dynamic instability appears due to the pump of energy from the Lorentz force [1]
- An alternative configuration to avoid this type of instability is to spin the EDT
- Additionally, the spinning feature provides more flexibility to the EDT orientation relative to $\boldsymbol{B}$, particularly important for high-inclined orbits, where vertically aligned EDTs are less effective [2]



[1] J. Pelaez, E. C. Lorenzini, O. López-Rebollal, and M. Ruiz, "A new kind of dynamic instability in electrodynamic tethers," *J. Astronaut. Sci.*, vol. 48, no. 4 ,pp. 449–476, 2000
[2] J. Pearson, J. Carroll, and E. Levin, "An update on EDDE, the ElectroDynamic Delivery Express," in Proc. 5th Int. Conf. Tethers Space, Michigan, USA, 2016

Motivation & State of the Art

- The selection of the spin plane is a critical aspect to reach high-performances with spinning EDTs [2,3]
- However, this spin plane is affected by external disturbances, such as gravity gradient, Lorentz force, etc
- When gravity gradient perturbations are included, the analysis of the dynamics of spinning EDTs diverges from that of typical satellites due to elasticity properties, inability to compression and negligible axial moment of inertia
- Knowledge remains scarce due to the low number of spinning tether missions
- Studies mainly focused on transverse and axial vibrations[4,5]
- Only a few works analyzed the attitude dynamics, but always restricted to planar motion and/or circular orbit [6,7]

[2] J. Pearson, J. Carroll, and E. Levin, "An update on EDDE, the ElectroDynamic Delivery Express," in Proc. 5th Int. Conf. Tethers Space, Michigan, USA, 2016

[3] J. Simon-Aznar, G. Sanchez-Arriaga, and B. Vatankhahghadim, "Optimal spin plane and performance of spinning electrodynamic tethers for orbital maneuvering," *J. Guid. Control Dyn.*, submitted, 2025

[4] V.A. Chobotov, "Gravity-Gradient Excitation of a Rotating Cable-Counterweight Space Station in Orbit", J. of Applied Mech. 1963, vol. 30, pp. 547–554

[5] V.A. Chobotov, "Gravitational excitation of an extensible dumbbell satellite", J. of Spacecraft and Rockets, 1967, vol. 4, no. 10, pp. 1295–1300

[6] P.M. Bainum, and K.S. Evans, "Gravity-Gradient Effects on the Motion of Two Rotating Cable-Connected Bodies", AIAA Journal, 1976, vol. 14, no. 1, pp. 26–32.

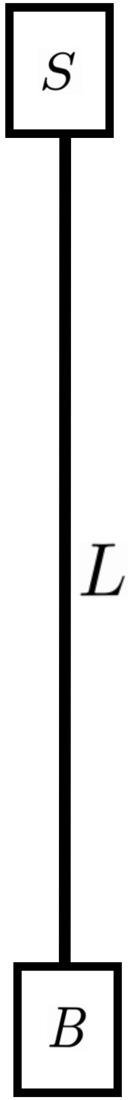
[7] J.R. Ellis, and C.D. Hall, "Out-of-Plane Librations of Spinning Tethered Satellite Systems", Celest. Mech. and Dyn. Astronomy, 2010, vol. 106, no. 1, p. 39, issn 1572-9478

Model

- Straight, rigid and inert tether of mass m_t and length L that joins two end masses m_S and m_B

- Null moment of inertia along tether's direction

- The motion of the center of mass is prescribed and follows an unperturbed Keplerian orbit of inclination i and eccentricity e. For simplicity, we assume zero right ascension of the ascending node and argument of perigee



Frames of Reference

Inertial Frame

❖ An inertial frame with origin at the center of the Earth

1. $\boldsymbol{i}_{\mathrm{I}}$ pointing to the Aries point
2. $\boldsymbol{k}_{\mathrm{I}}$ along the direction of rotation of the Earth
3. $\boldsymbol{j}_{\mathrm{I}} = \boldsymbol{k}_{\mathrm{I}} \times \boldsymbol{i}_{\mathrm{I}}$

Orbital Frame

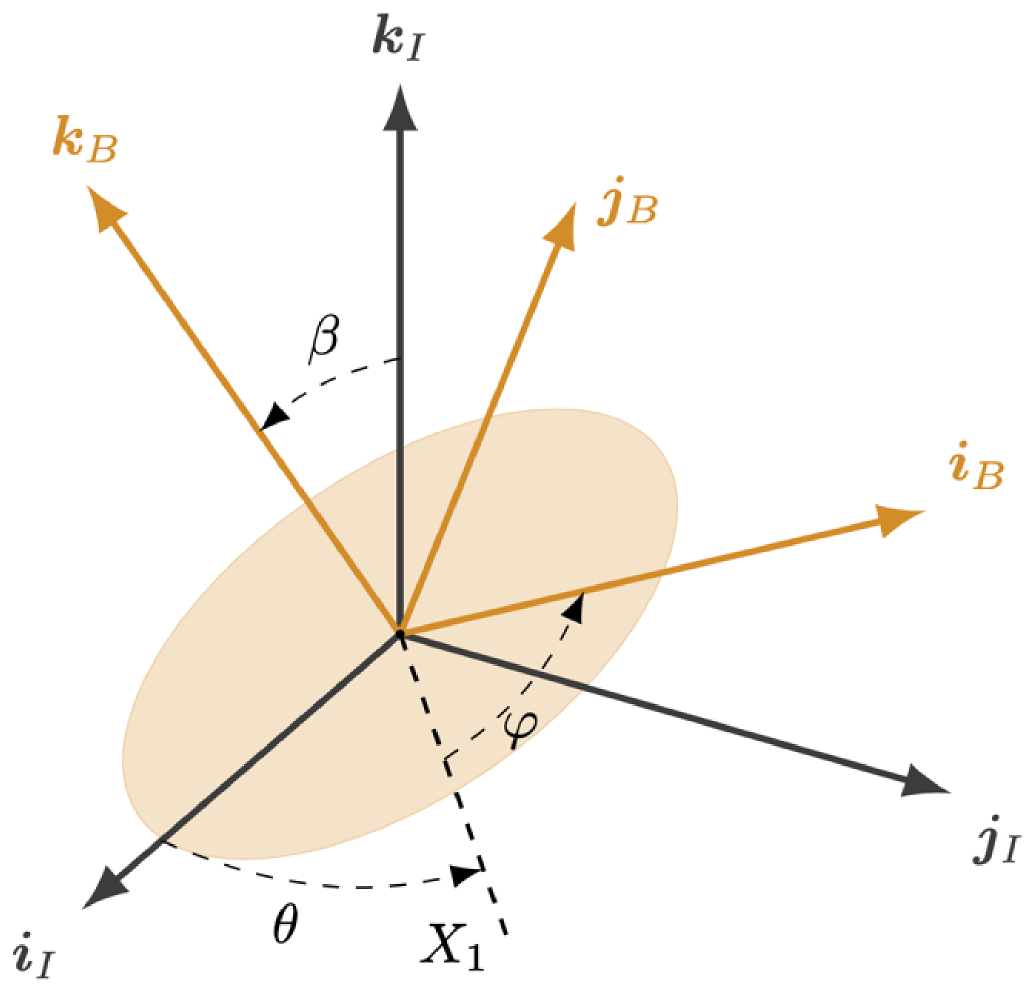
❖ An orbital frame with origin at the center of mass of the tether system

1. $\boldsymbol{i}_{\mathrm{O}}$ pointing to the zenith
2. $\boldsymbol{k}_{\mathrm{O}}$ normal to the orbital plane
3. $\boldsymbol{j}_{\mathrm{O}} = \boldsymbol{k}_{\mathrm{O}} \times \boldsymbol{i}_{\mathrm{O}}$

Frames of Reference

❖We use the Euler angles θ, β, φ in 3-1-3 sequence to determine the attitude of the body frame relative to the inertial frame

1. $\boldsymbol{i}_B$ along the tether's direction
2. $\boldsymbol{k}_B$ perpendicular to the spin plane
3. $\boldsymbol{j}_B = \boldsymbol{k}_B \times \boldsymbol{i}_B$



Attitude Dynamics Equations

❖From the angular momentum equation

$$\left.\frac{d\boldsymbol{H_c}}{dt}\right|_{\mathrm{I}} = \boldsymbol{M_c}$$

Where $\boldsymbol{H}_{\mathrm{c}}$ is the angular momentum vector and $\boldsymbol{M}_{\mathrm{c}}$ the external torque about the system's center of mass

❖The system's angular velocity relative to the inertial frame

$$\boldsymbol{\Omega}_{BI} = \Omega_{\parallel}\boldsymbol{i}_B + \boldsymbol{i}_B \times \frac{d\boldsymbol{i}_B}{dt} = \Omega_{\parallel}\boldsymbol{i}_B + \left|\frac{d\boldsymbol{i}_B}{dt}\right|\boldsymbol{k}_B \equiv \Omega_{\parallel}\boldsymbol{i}_B + \Omega_{\perp}\boldsymbol{k}_B$$

Attitude Dynamics Equations

❖One can find the attitude equations [8]

$$\frac{d\theta}{d\tau} = -\frac{\widetilde{\boldsymbol{M}}_c \cdot \boldsymbol{j}_B}{\widetilde{\Omega}_\perp} \frac{\sin\varphi}{\sin\beta}$$

$$\frac{d\beta}{d\tau} = -\frac{\widetilde{\boldsymbol{M}}_c \cdot \boldsymbol{j}_B}{\widetilde{\Omega}_\perp} \cos\varphi$$

$$\frac{d\varphi}{d\tau} = \widetilde{\Omega}_\perp + \frac{\widetilde{\boldsymbol{M}}_c \cdot \boldsymbol{j}_B}{\widetilde{\Omega}_\perp} \frac{\sin\varphi}{\tan\beta}$$

$$\frac{d\widetilde{\Omega}_\perp}{d\tau} = \widetilde{\boldsymbol{M}}_c \cdot \boldsymbol{k}_B$$

Where

❖ $\widetilde{\boldsymbol{M}}_c \equiv \boldsymbol{M}_c/(\omega_O^2 I_c)$ is the dimensionless torque,

❖ I_c is the moment of inertia relative to a line perpendicular to the tether through the center of mass

❖ ω_O is the mean orbital motion

❖ $\tau = \omega_O t$ is the dimensionless time

❖ $\widetilde{\Omega}_\perp = \Omega_\perp/\omega_O$ is the normalized spin rate

[8] J. Pelaez, M. Sanjurjo-Rivo, F. R. Lucas, M. Lara, E. C. Lorenzini, D. Curreli, and D. J. Scheeres, “Dynamics and stability of tethered satellites at Lagrangian points,” ESTEC, ESA Tech. Rep., 2008.

Attitude Dynamics Equations

- Assuming that gravity gradient is the only perturbation, which is given by

$$\widetilde{\boldsymbol{M}}_c^g \approx K(\boldsymbol{i}_B \cdot \boldsymbol{i}_O)(\boldsymbol{i}_B \times \boldsymbol{i}_O)$$

Where

$$K(\nu) = 3\left(\frac{1 + e\cos\nu}{1 - e^2}\right)^3$$

$$\frac{d\theta}{d\tau} = \frac{K}{\widetilde{\Omega}_\perp}(\boldsymbol{k}_B \cdot \boldsymbol{i}_O)(\boldsymbol{i}_B \cdot \boldsymbol{i}_O)\frac{\sin\varphi}{\sin\beta}$$

$$\frac{d\beta}{d\tau} = \frac{K}{\widetilde{\Omega}_\perp}(\boldsymbol{k}_B \cdot \boldsymbol{i}_O)(\boldsymbol{i}_B \cdot \boldsymbol{i}_O)\cos\varphi$$

$$\frac{d\varphi}{d\tau} = \widetilde{\Omega}_\perp - \frac{K}{\widetilde{\Omega}_\perp}(\boldsymbol{k}_B \cdot \boldsymbol{i}_O)(\boldsymbol{i}_B \cdot \boldsymbol{i}_O)\frac{\sin\varphi}{\tan\beta}$$

$$\frac{d\widetilde{\Omega}_\perp}{d\tau} = K(\boldsymbol{j}_B \cdot \boldsymbol{i}_O)(\boldsymbol{i}_B \cdot \boldsymbol{i}_O)$$

Dynamics of Fast Spinning Tethers

- Under the assumption of fast spinning tether, the spin angular velocity is much larger than the orbital angular velocity ($\tilde{\Omega}_\perp = \Omega_\perp / \omega_O \gg 1$)
- The timescale of variation of θ, β is larger than of the fast variable φ
- We can average the dynamics equations over one tether revolution to find the slow evolution

Dynamics of Fast Spinning Tethers

$$\left.\begin{aligned}\frac{d\theta}{d\nu} &\approx \frac{1}{2}\frac{\widetilde{K}}{\widetilde{\Omega}_\perp}\frac{1}{\sin\beta}\left(\frac{S^2-P^2}{2}\sin 2\beta - SP\cos 2\beta\right)\\ \frac{d\beta}{d\nu} &\approx \frac{1}{2}\frac{\widetilde{K}}{\widetilde{\Omega}_\perp}F(S\cos\beta + P\sin\beta)\end{aligned}\right\}\ \text{Decoupled from } \varphi$$

Where

$$\widetilde{K}(\nu) = 3(1+e\cos\nu)/(1-e^2)^{3/2}$$

$$P \equiv \cos\nu\sin\theta - \cos i\ \cos\theta\sin\nu$$

$$S \equiv \sin i\ \sin\nu$$

$$F \equiv \cos\nu\cos\theta + \cos i\sin\nu\sin\theta$$

$$\frac{d\varphi}{d\nu} \approx \widetilde{\Omega}_\perp - \frac{d\theta}{d\nu}\cos\beta$$

$$\frac{d\widetilde{\Omega}_\perp}{d\nu} \approx 0 \longrightarrow \widetilde{\Omega}_\perp = \text{constant}$$

Spin Plane Dynamics

❖The attitude dynamics of the spin plane is governed by the evolution of θ, β

$$\frac{d\theta}{d\nu} = \frac{1}{2}\frac{\widetilde{K}}{\widetilde{\Omega}_\perp}\frac{1}{\sin\beta}\left(\frac{S^2 - P^2}{2}\sin 2\beta - SP\cos 2\beta\right)$$

$$\frac{d\beta}{d\nu} = \frac{1}{2}\frac{\widetilde{K}}{\widetilde{\Omega}_\perp}F(S\cos\beta + P\sin\beta)$$

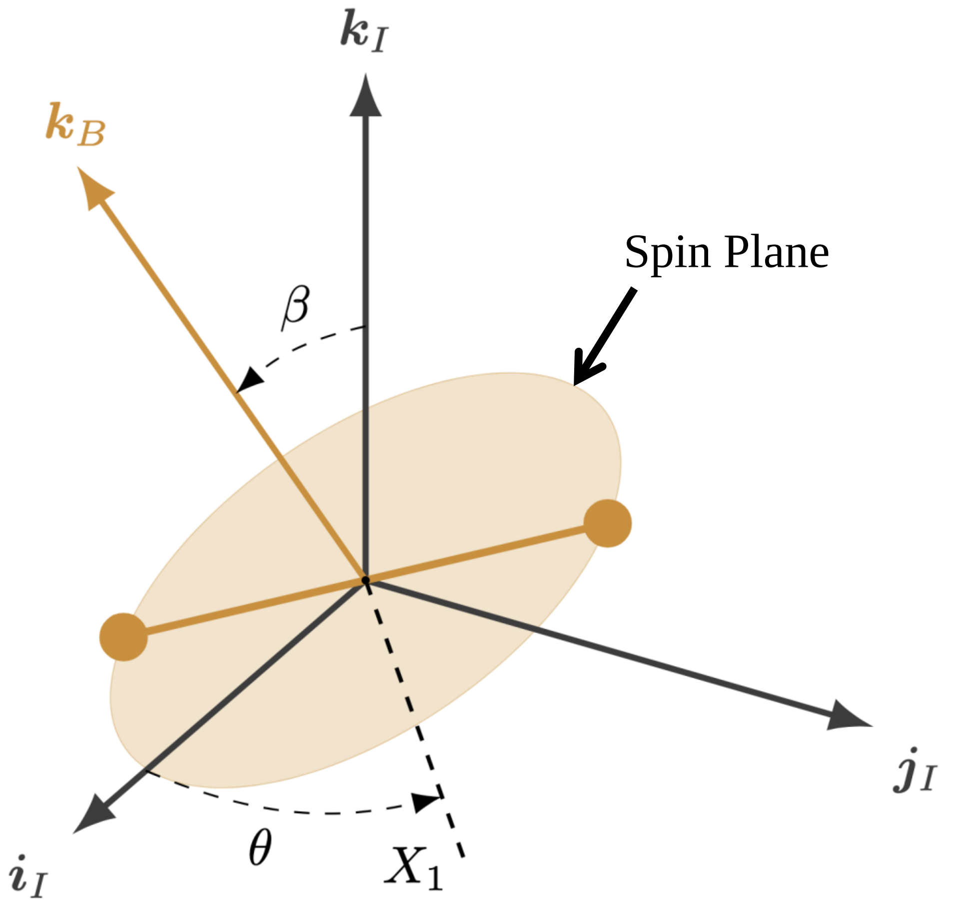
With

$$\widetilde{K}(\nu) = 3(1 + e\cos\nu)/(1 - e^2)^{3/2}$$

$$P \equiv \cos\nu\sin\theta - \cos i\ \cos\theta\sin\nu$$

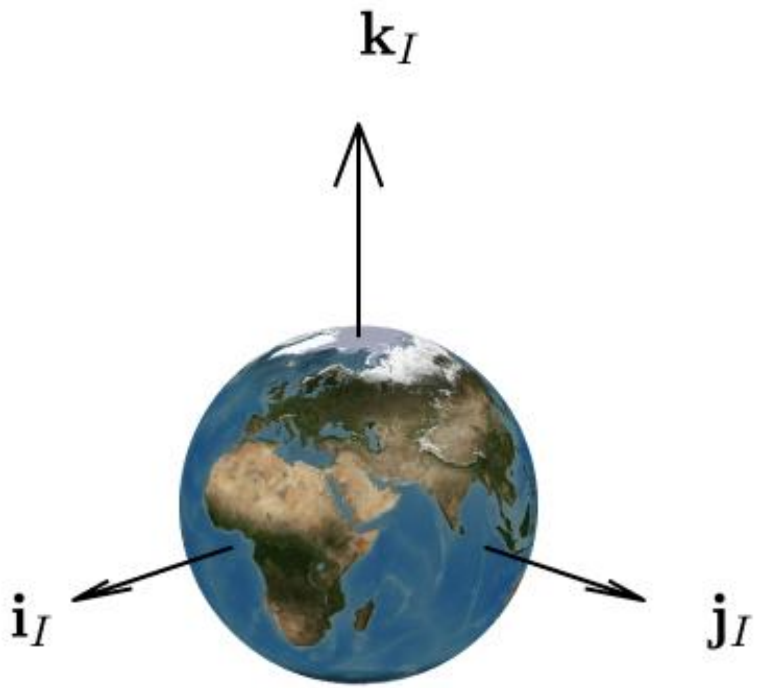
$$S \equiv \sin i\ \sin\nu$$

$$F \equiv \cos\nu\cos\theta + \cos i\ \sin\nu\sin\theta$$



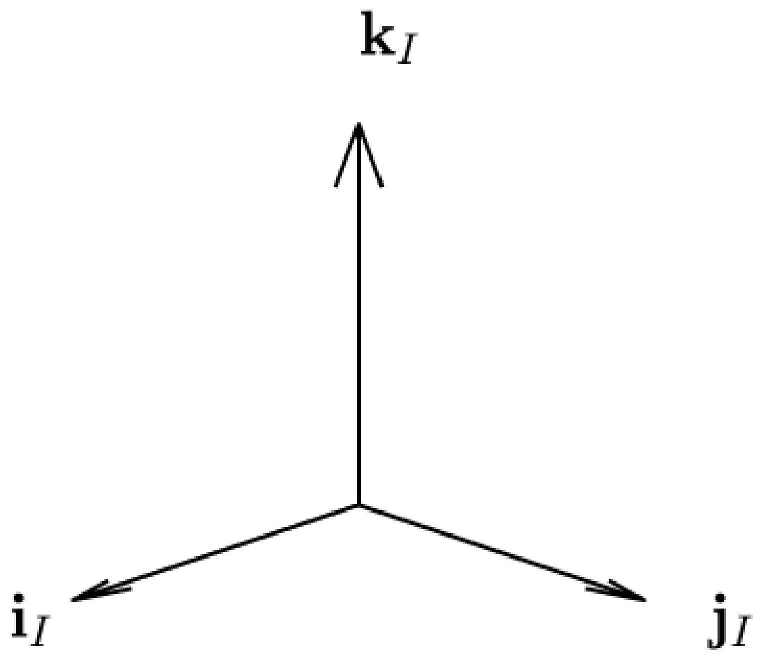
Spin Plane Dynamics

❖ Earth-centered Inertial Frame



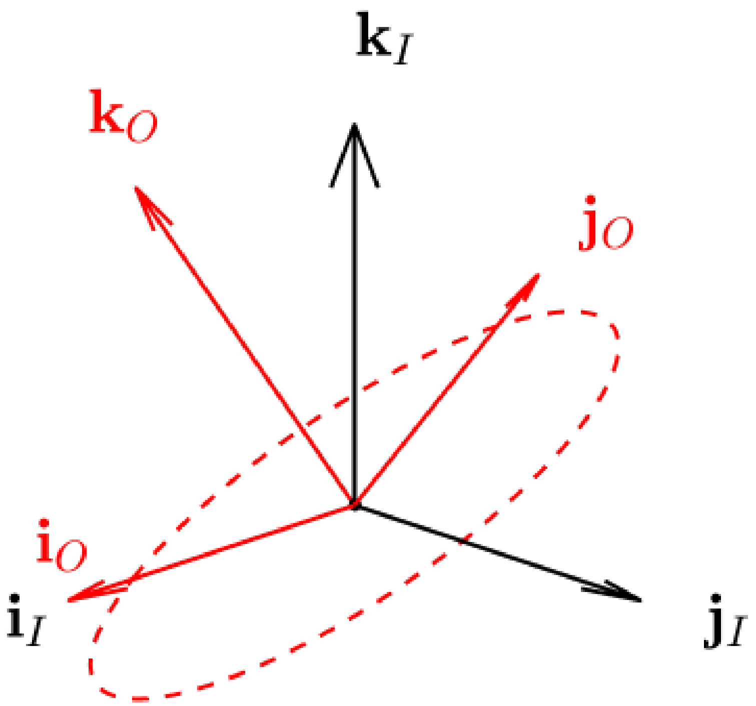
Spin Plane Dynamics

- ~~Earth~~-centered Inertial Frame



Spin Plane Dynamics

- ~~Earth-centered Inertial Frame~~
- Orbital Frame with $\mathrm{i} = 50°$



Spin Plane Dynamics

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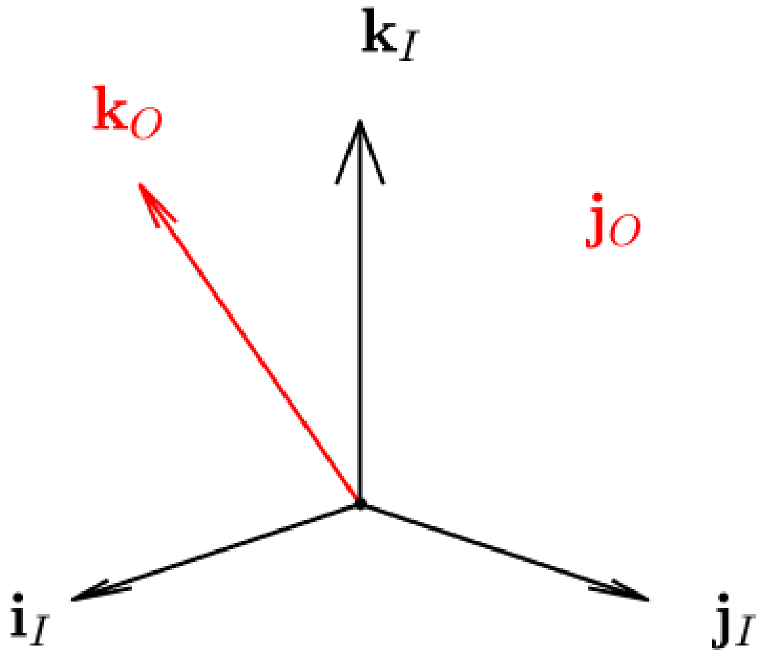
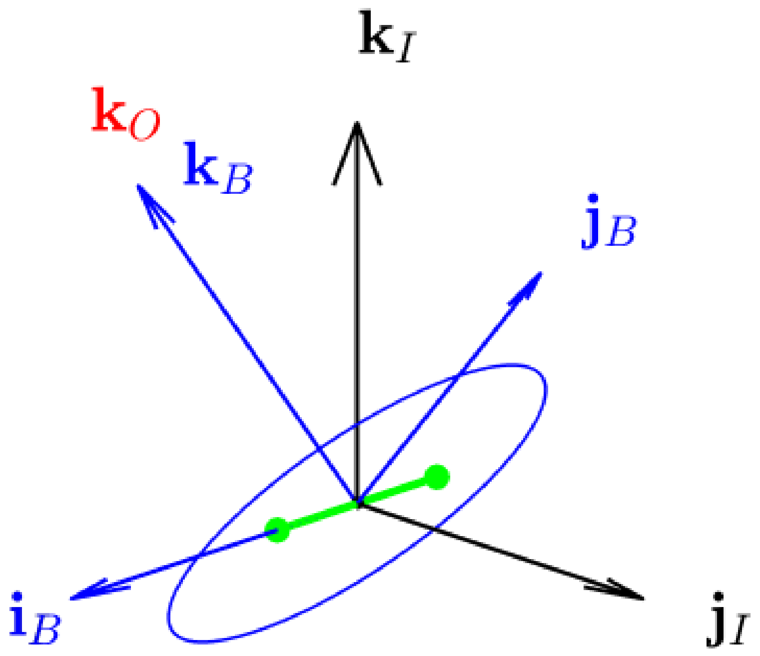


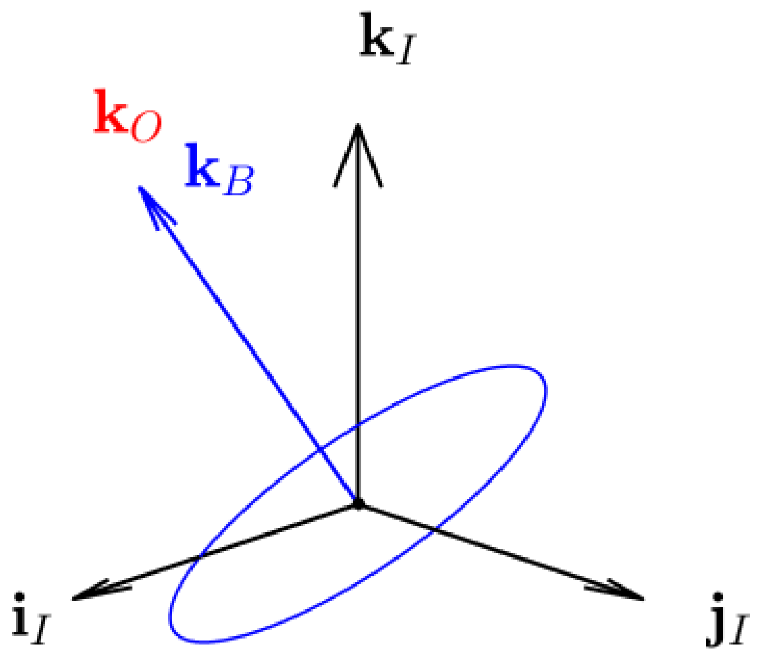
Spin Plane Dynamics

- ~~Earth~~-centered Inertial Frame
- Orbital Frame with $\mathrm{i} = 50°$
- Body Frame with $\theta = 0°$ and $\beta = \mathrm{i}$



Spin Plane Dynamics

- ~~Earth~~-centered Inertial Frame
- Orbital Frame with $\mathrm{i} = 50°$
- Body Frame with $\theta = 0°$ and $\beta = \mathrm{i}$
- We show the spin plane evolution for $e = 0.75$ and different initial conditions:



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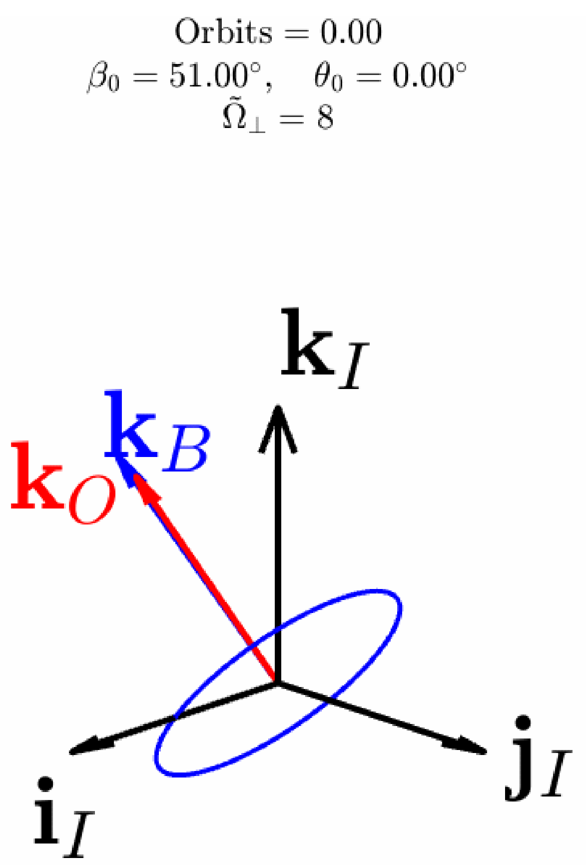
- We show the spin plane evolution for $e = 0.75$ and different initial conditions:
  I. $\theta_0 = 0°$, $\beta_0 = 51°$ and $\tilde{\Omega}_\perp = 8$



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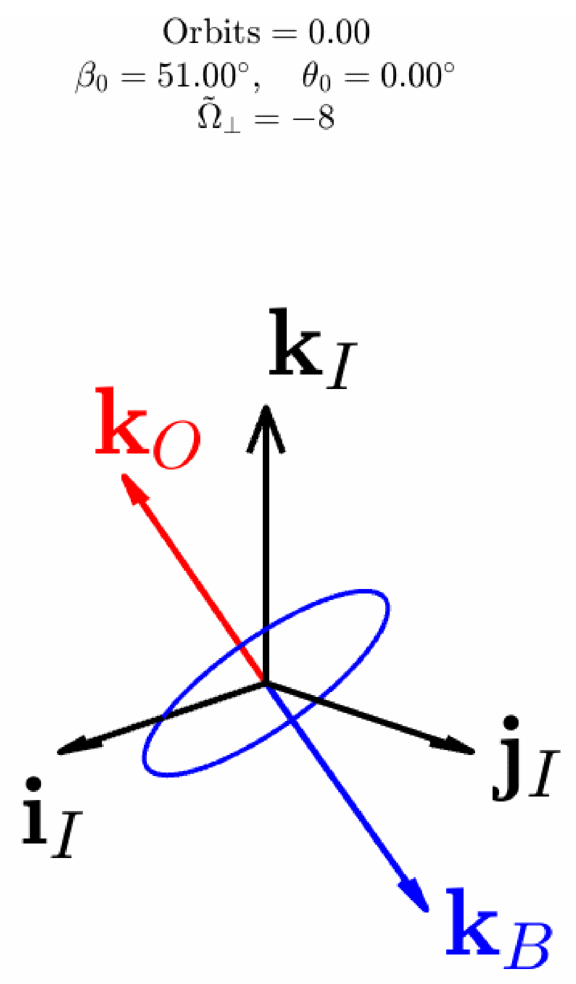
    II. $\theta_0 = 0°$, $\beta_0 = 51°$ and $\tilde{\Omega}_\perp = -8$



Spin Plane Dynamics

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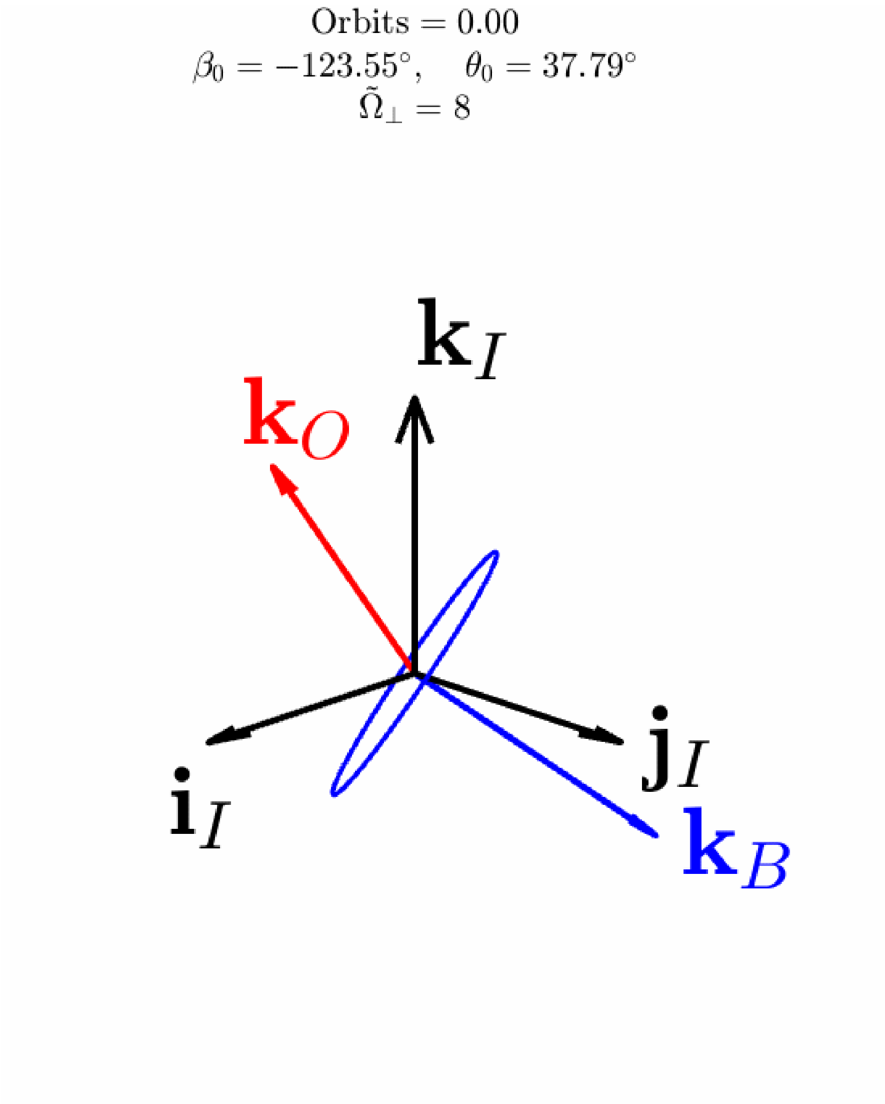
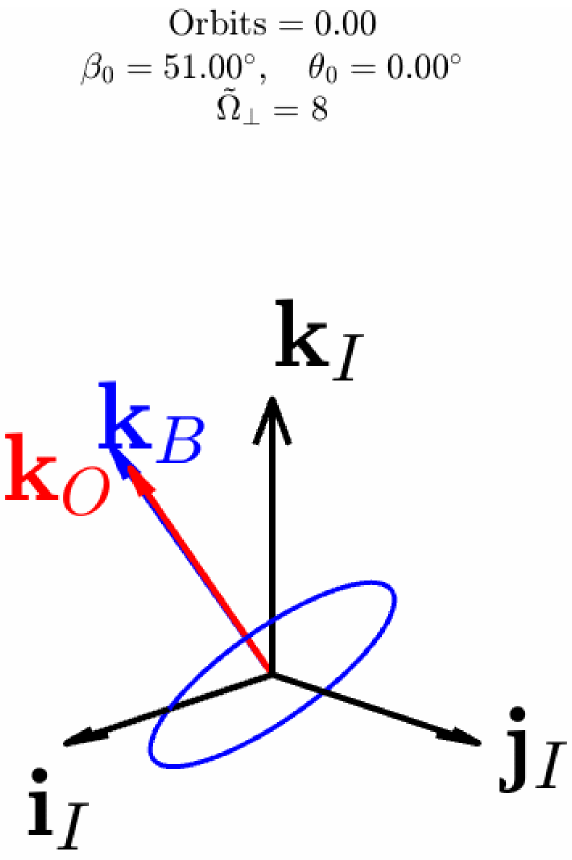
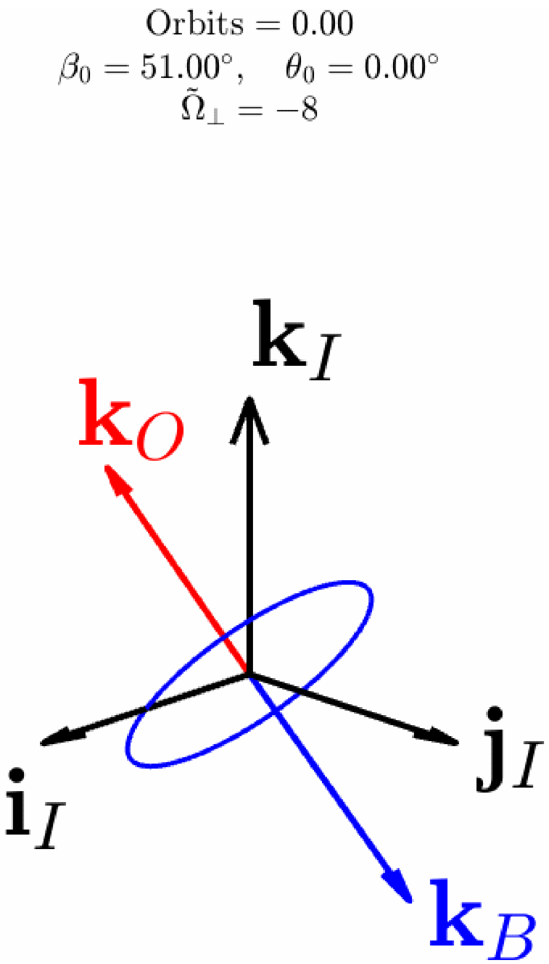
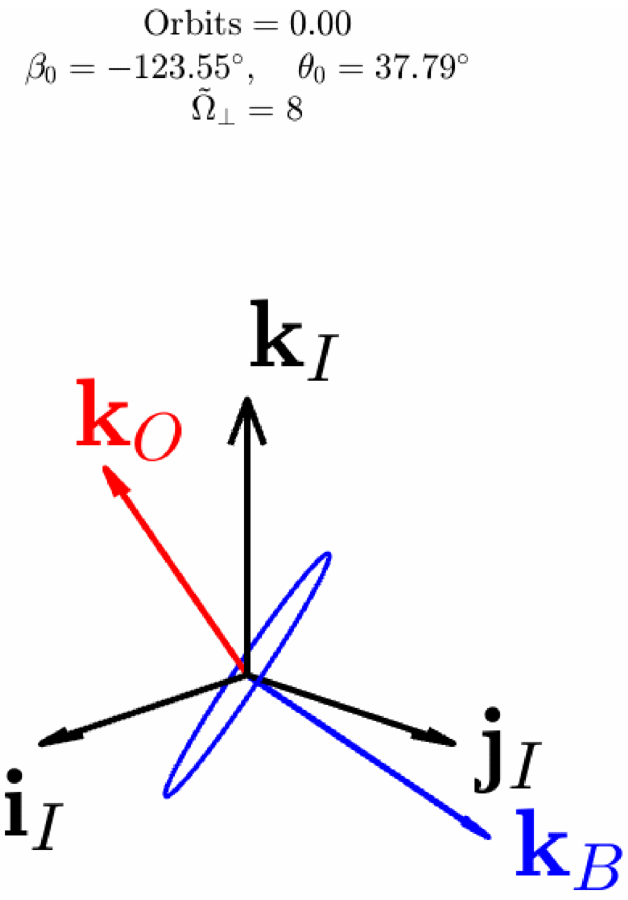
  - *I.* $\theta_0 = 0°$, $\beta_0 = 51°$ and $\tilde{\Omega}_\perp = 8$
  - *II.* $\theta_0 = 0°$, $\beta_0 = 51°$ and $\tilde{\Omega}_\perp = -8$
  - *III.* $\theta_0 = 37.79°$, $\beta_0 = -123.55°$ and $\tilde{\Omega}_\perp = 8$



Spin Plane Dynamics







- Stable Equilibrium
- Unstable Equilibrium
- Periodic Orbit

Research Objectives

❖ Analysis of optimal spin plane configurations

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- Analysis of optimal spin plane configurations
- Study of the dynamics of fast-spinning inert tethers
- Study of the dynamics of spinning EDTs (that is, including electrodynamic forces)
- Control laws analysis and development of algorithms for spinning EDTs systems
- High-fidelity simulations for study cases of interest

Achievements

Dissemination

- ✓ 9th European Conference on Space Debris, 1-5 April 2025, Bonn, Germany, "Performance, Navigation and Control of a Spinning Electrodynamic Tether System".
- ✓ 30th International Symposium on Space Flight Dynamics, 1-5 June 2026, Toulouse, France, "Spin Plane Dynamics of Fast Spinning Tethers".

Publication

- ✓ SIMON-AZNAR, J.; SANCHEZ-ARRIAGA, G.; VATANKHAHGHADIM, B., "Optimal Spin Plane and Performance of Spinning Electrodynamic Tethers for Orbital Maneuvering". **Journal of Guidance, Control, and Dynamics**. 2026, pp. 1–9. Available from **doi: 10.2514/1.G009572**.

Others

- ✓ Volunteering in EuroGNC conference, 5-7 May 2026, Madrid.
- ✓ 6th Exchange Workshop: "Symbolic Computing with Sympy". 1 December 2025.
- ✓ 5th Exchange Workshop: "Reference Management and Note Taking Best Practices". 10 June 2025.
- ✓ 4th Exchange Workshop: "GitHub, VS Code and Copilot". 25 November 2024.
- ✓ Specialization Course: "An Introduction to Statistical and Variational Methods Assimilation and Real Time Modeling". 2 June 2025.

Thank you!

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