Presentation of admission to 3rd year

PhD Student	PASTORE GUIDO
Supervisor	PROF. E. LORENZINI
Co-Supervisor	PROF. S. DEBEI

PhD Course in *Scienze, tecnologie e misure spaziali*
Curricolo *Misure Meccaniche per l'ingegneria e lo spazio*
XXX Cycle

Deorbit targets

25-year deorbit on future objects launched to space would lead in 100 years to **< 10 catastrophic collisions** instead than **more than 50 with business-as-usual scenario** (Klinkrad H., 2006) ⇨

294 mission-related objects left in **GTO** between 2004 and 2012**: only 43 reentered** (Fisher, S. and David, E., 2014)

Dual-payload adapters are a **threat to operational satellites: mass** of about **500 kg** and **very large exposed area.**

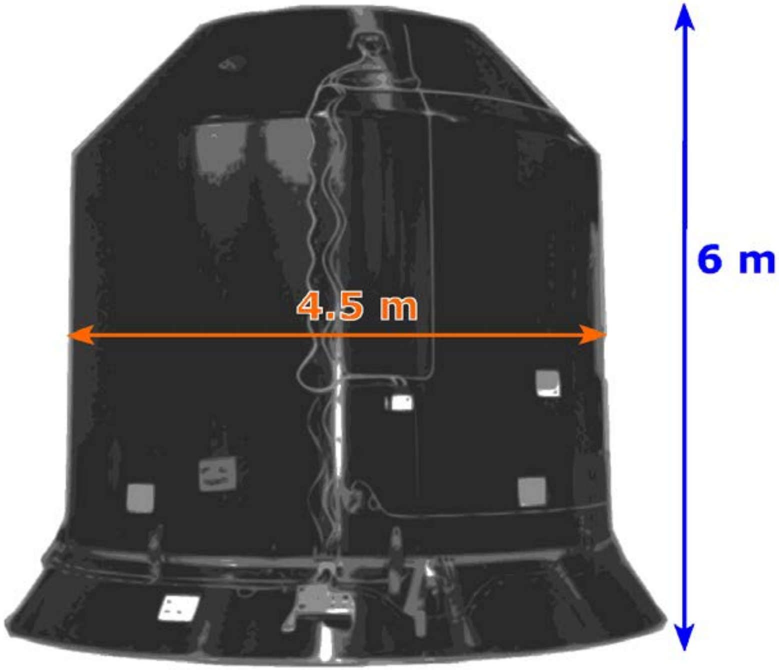
Example: *Sylda,* used in *Ariane5,* left in GTO.

Deorbit from GTO has a **high commercial relevance**

Only in 2014:
5 launches with Ariane5,
all of them to GEO (Ref. . http://www.spacelaunchreport.com/log2015.html)

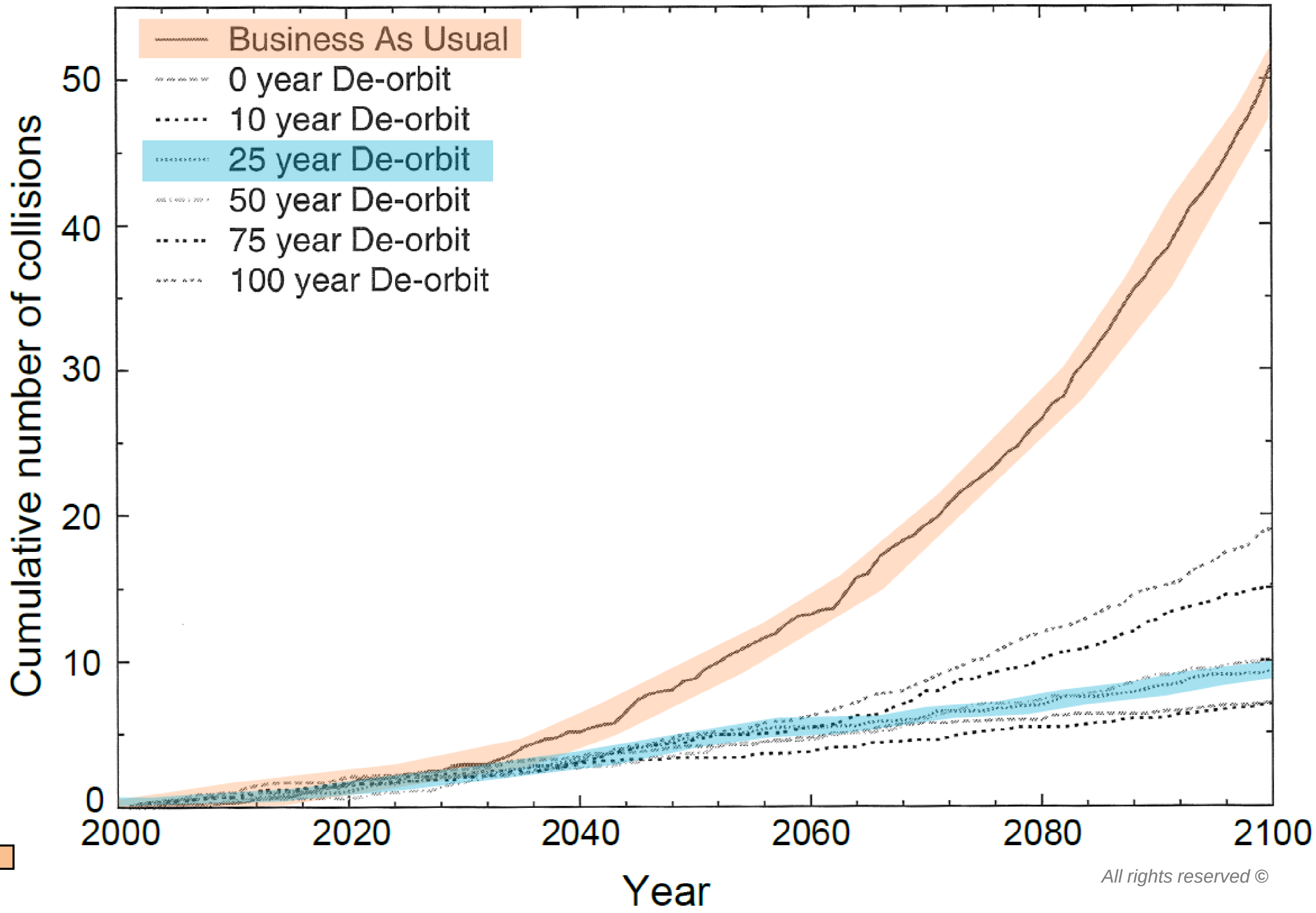
Main solutions attempted:

- **lower perigee, 200 kg less** onboard **Ariane 5**
- **launch in favorable Sun-synchronous resonance conditions:** no warranty of deorbit time lower than 25 years



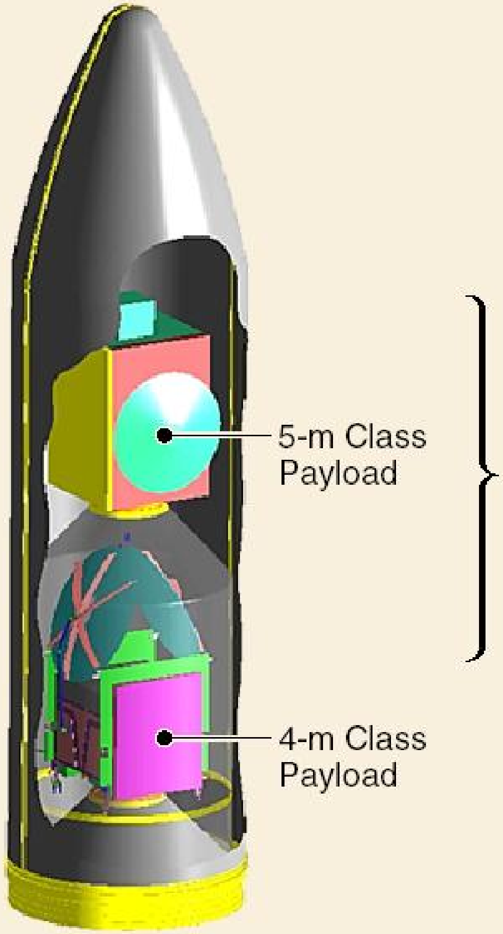
© *Courtesy of ESA*

Orbital Debris problem



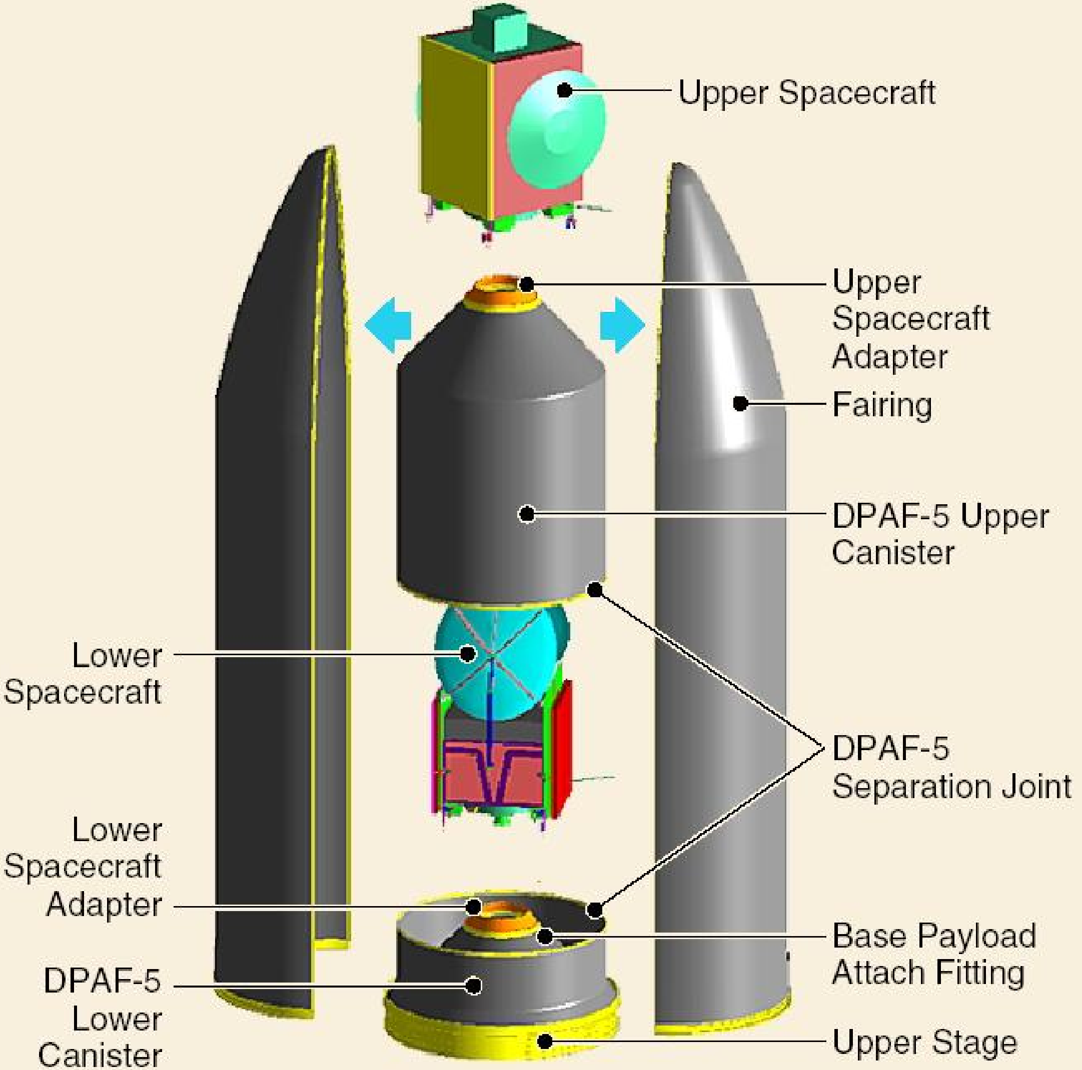
All rights reserved ©

Ariane 5 dual payload and *Sylda*


5-m Class Payload

4-m Class Payload

Cutaway View of Encapsulated Payloads


Upper Spacecraft

Upper Spacecraft Adapter

Fairing

DPAF-5 Upper Canister

Lower Spacecraft

DPAF-5 Separation Joint

Lower Spacecraft Adapter

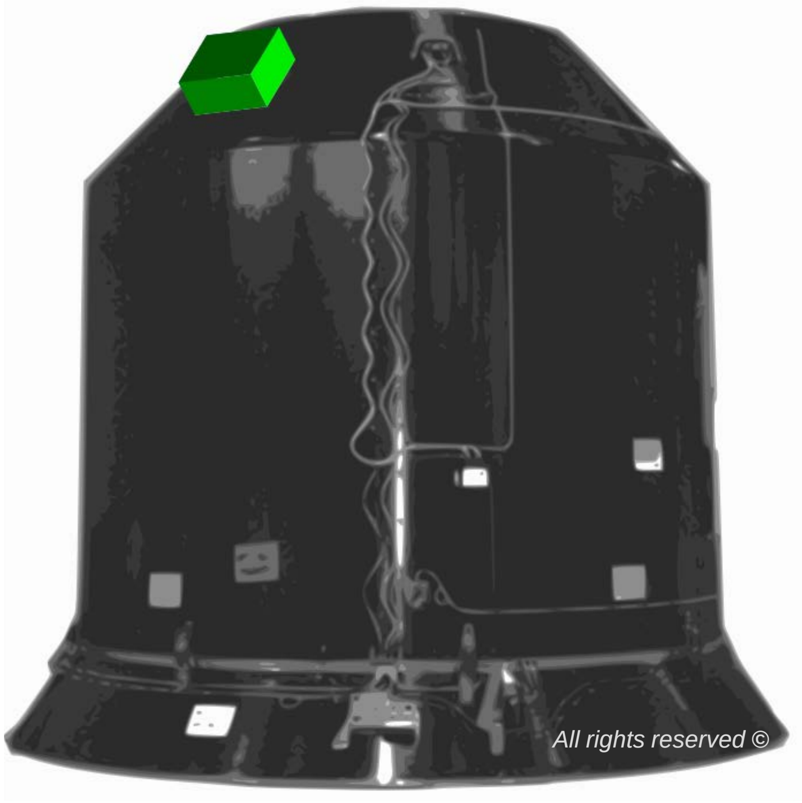
Base Payload Attach Fitting

DPAF-5 Lower Canister

Upper Stage

Expanded View

Placement of de-orbit module & deployment strategy


All rights reserved ©

Tether reeled up around a drum wheel and stored in a dedicated box, attached to Sylda on the upper part

- integration to Sylda is much easier, the occupied space is more distant from the fairing's walls

- can sustain much better vibrational loads at launch

- the deployment is much easier

- A single box with everything inside creates an displacement of center of mass of the launch system. For double tether configuration, this issue is more easily solved placing two boxes of equal mass.

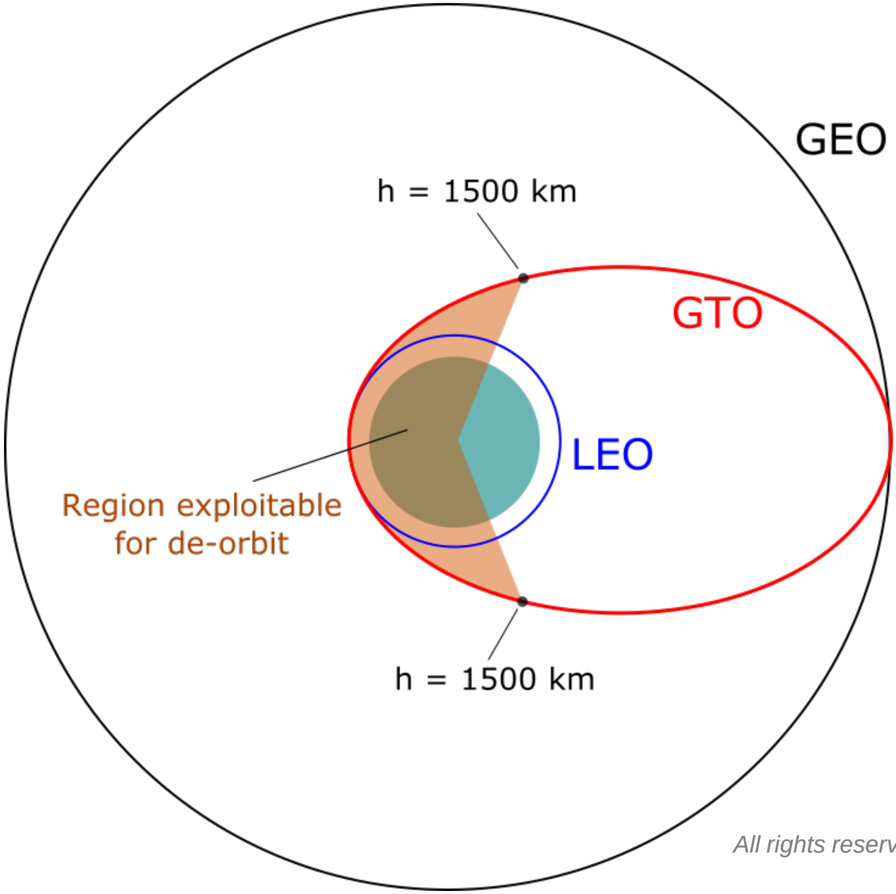
Deployment strategy:

Deployment must be started with an initial impulse (such as a mechanical spring system) and then helped with a small dedicated motor that can be powered with electrical current passively generated along the tether.

Numerical model of De-orbit from GTO (presented at conference *Tethers in Space 2016*)

Why GTO?

Not explored yet in literature. Predictable applicability to all dual-payload launches to GEO. Possibility of exploiting local rotation for tether attitude stability.



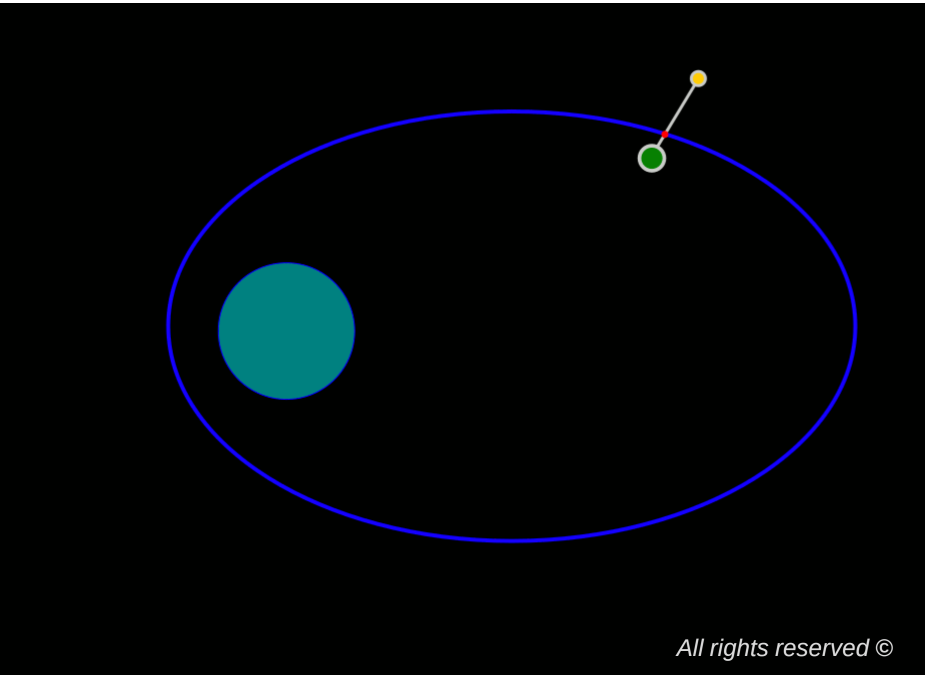
All rights reserved ©

De-orbit computed in the code only when the system is orbiting below 1500 km: **need sufficient electron density and atmospheric density**

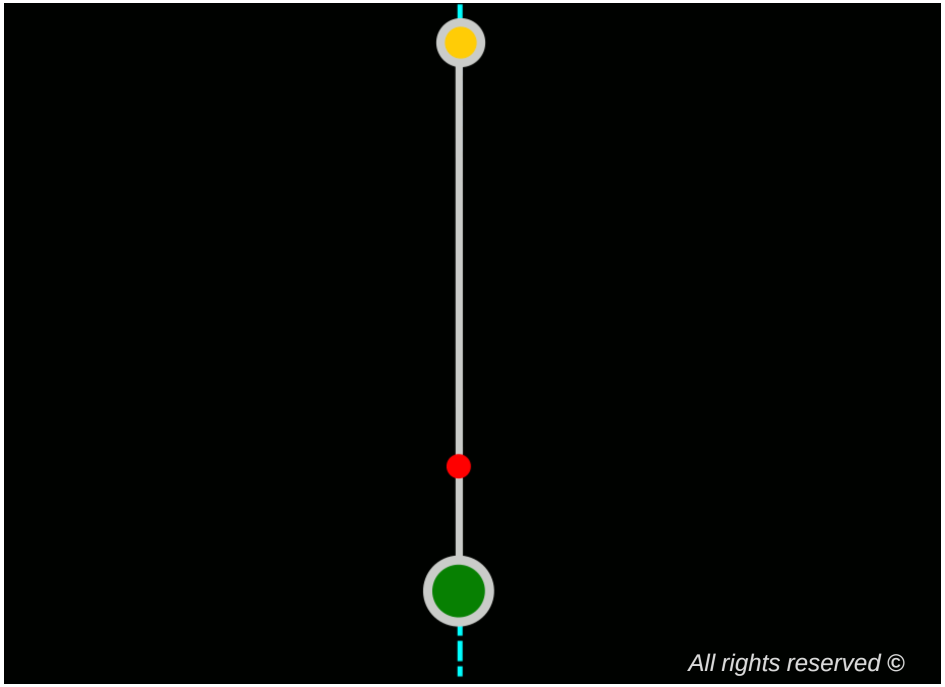
Global and local motion

Global deorbit path:
Change in orbital parameters at every computational step during de-orbit. De-orbit is active only when altitude is below 1500 km.

Local in-Plane Rotation
Profile of in-plane libration angle and angular velocity. Spin motion is exploited for tether's attitude stabilization.



All rights reserved ©



All rights reserved ©

Physical model – part 1

Dumbbell with **rigid conductive bare electrodynamic tape tether**, and **point masses** at anodic tip A, with a tip mass, and cathodic tip C, where the cathode and the object to deorbit are placed

Zero orbital inclination

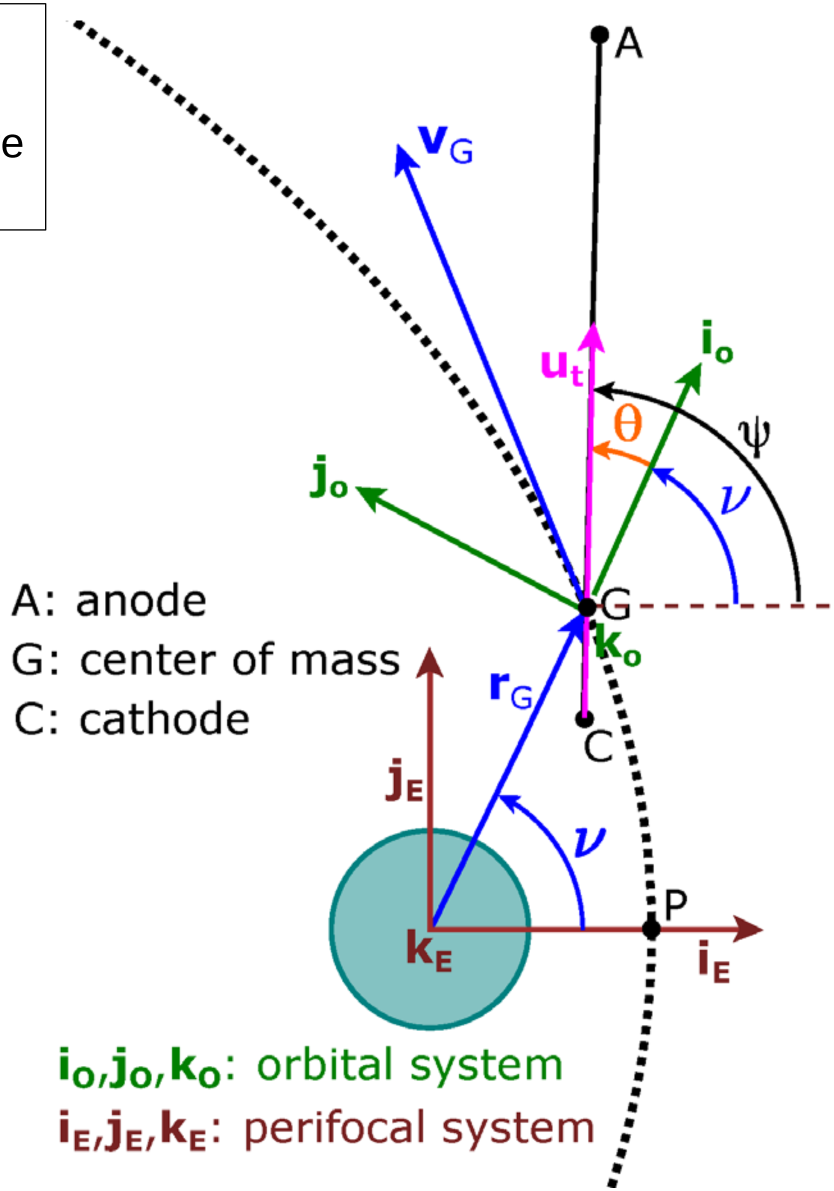
Only in-plane rotation and related dynamics is considered

Conventional current flows from C to A, directed as the motional electric field along the tether, unit vector $\mathbf{u}_t$

Normalized parameters and equations are used for higher versatility of the model and computational efficiency, following the notation by *Peláez et al.*

Normalized parameters (Λ_t, ϕ) are used, where:

$\Lambda_t = m_t / m$	ratio between tether mass and total mass
$X_G = L_t \cos^2 \phi$	distance between C and center of mass G

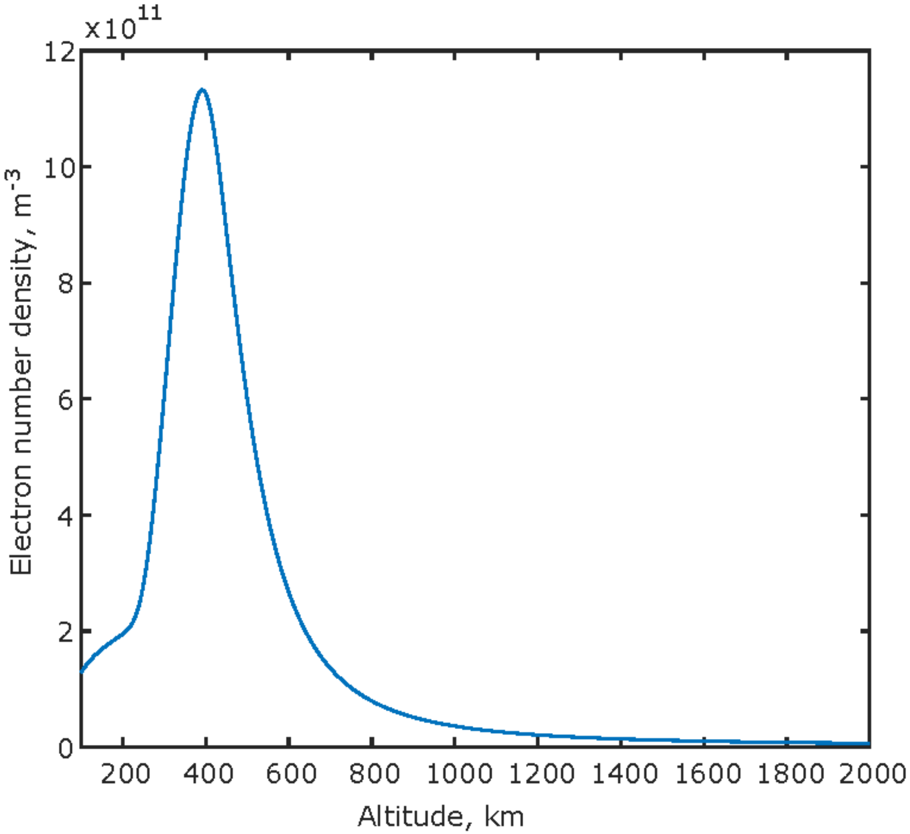


Physical model – part 2

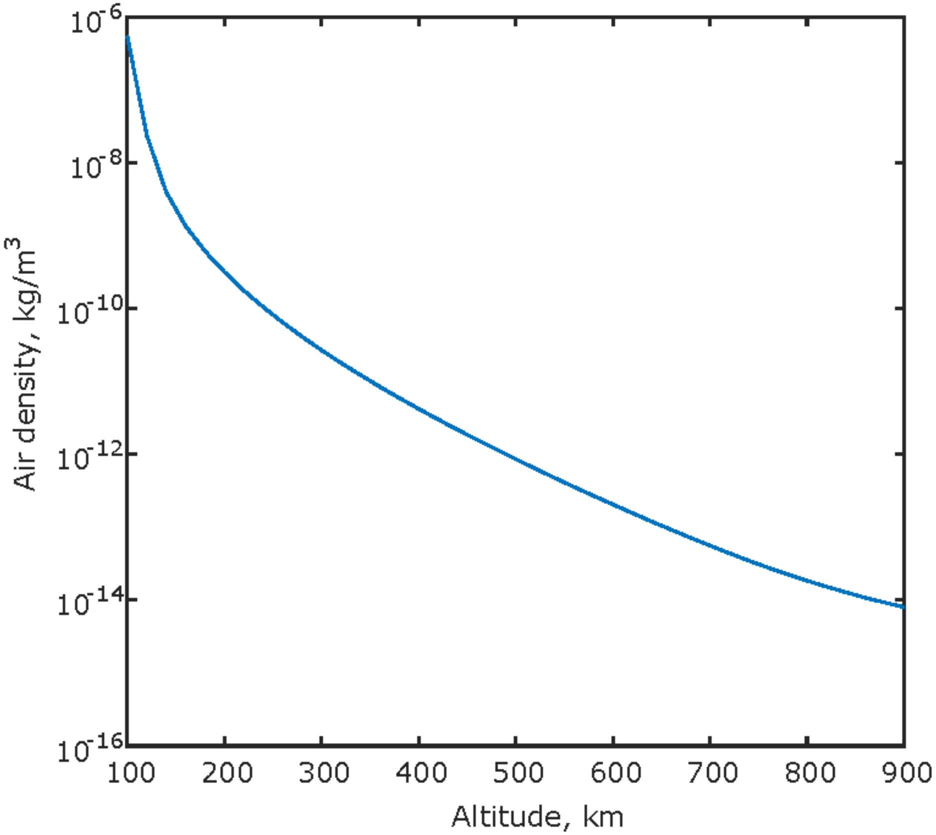
Dipole model is used for the **geomagnetic field**

Neglected local rotation with respect to orbital motion, atmosphere plays a lesser role than electrodynamics in torque generation ⇨ no atmospheric torque, **only Lorentz torque**.

IRI database from NASA is used for **plasma electron density**, with **average Solar flux**. Variation only with altitude.



Jacchia-Bowman 2008, with **average Solar flux**, is used for **air density**

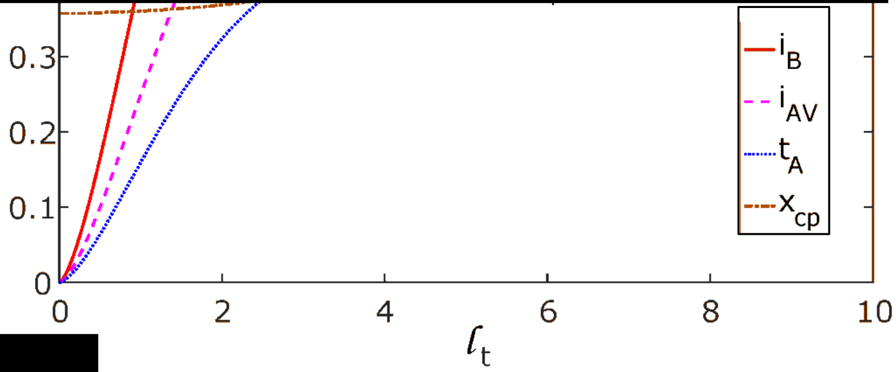


Physical model – part 3

[redacted]

Equations of system's dynamics
(Gauss eqs. from *Bate*, local rotation equation from *Beletsky*)

Orbital Motion Limited current collection
and
Ideal **Tether**
(zero cathodic impedance and voltage drop)



[redacted]

$) \; i_{av}$

Normalized perturbative force:
Lorentz drag and atmospheric drag

Normalized Lorentz torque about center of mass G

Tension at center of mass, divided by allowed tension from tether's material, including safety factor

Tether Mission Design

Aluminum 1100 is used as **conductive tether material** for simulations presented here. Model is valid also with other materials.
If using composite material with Aluminum matrix load margins are larger.

Simulations start at initial perigee.

Initial orbit is the orbit of a dual payload adapter that has a perigee high enough that it would not reenter in 25 years, and such that maximum launcher capacity is reached.
Perigee at 300 km and apogee at GEO altitude.

4 parameters determine univocally the **system's dynamics, and global and local motion:**

$\Lambda_t \uparrow$

Higher Lorentz drag , lower deorbit time , lower tension

Higher tether mass , less competitive technology

$\boxed{\Lambda_t = 0.03}$

$\dfrac{L_t}{h_t^{2/3}} \uparrow$

Higher current , higher Lorentz drag , lower deorbit time

Much higher normal stress on tether , much higher risk of tether breaking

$\boxed{L_t = 2km}$

$\boxed{h_t = 100\mu m}$

ϕ

Controls the mass distribution at tether tips. Used for parametric analysis. Phi ranges from: $\boxed{\phi_{\min} = \arcsin\left(\Lambda_t / 2\right)}$ to $\boxed{\phi_{\max} = \arccos\left(\Lambda_t / 2\right)}$ (Pelaez and Andrés, 2005) where min corresponds to ($m_C = 0$), and max to ($m_A = 0$).

$\boxed{\cos(\phi_0) = x_{cp,0}}$

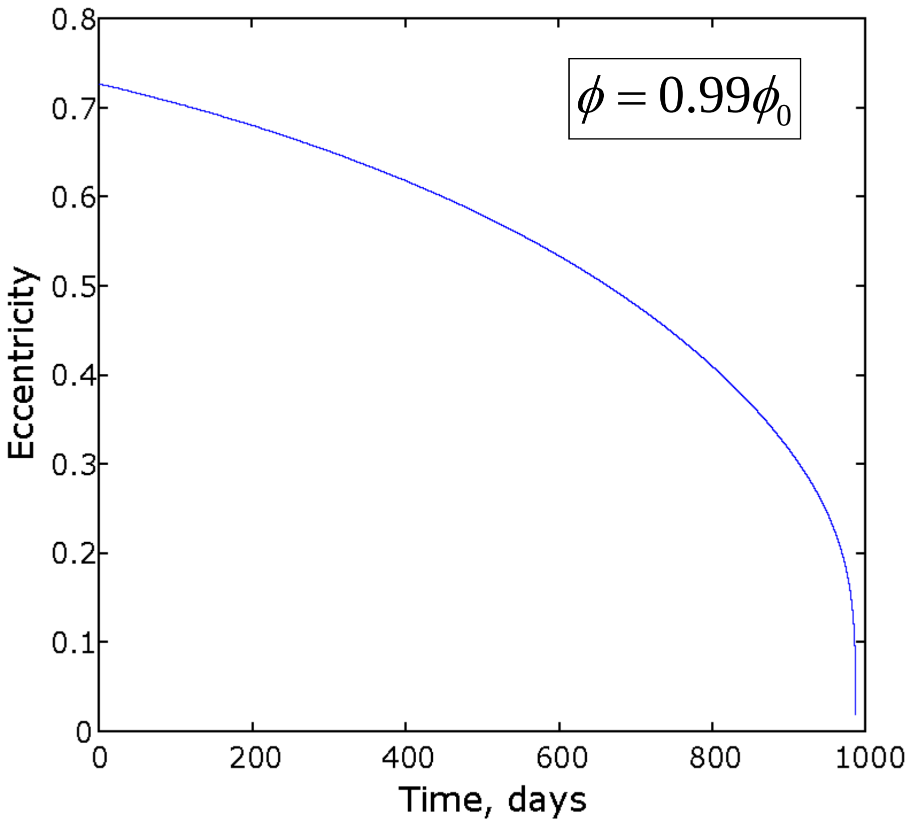
Self-balanced system: a tethered system with $\phi = \phi_0$, where ϕ_0 is the value that makes the Lorentz torque to vanish at initial perigee.
Such configuration already used to mitigate dynamic instability in librating tethers (Pelaez et al., 2000)

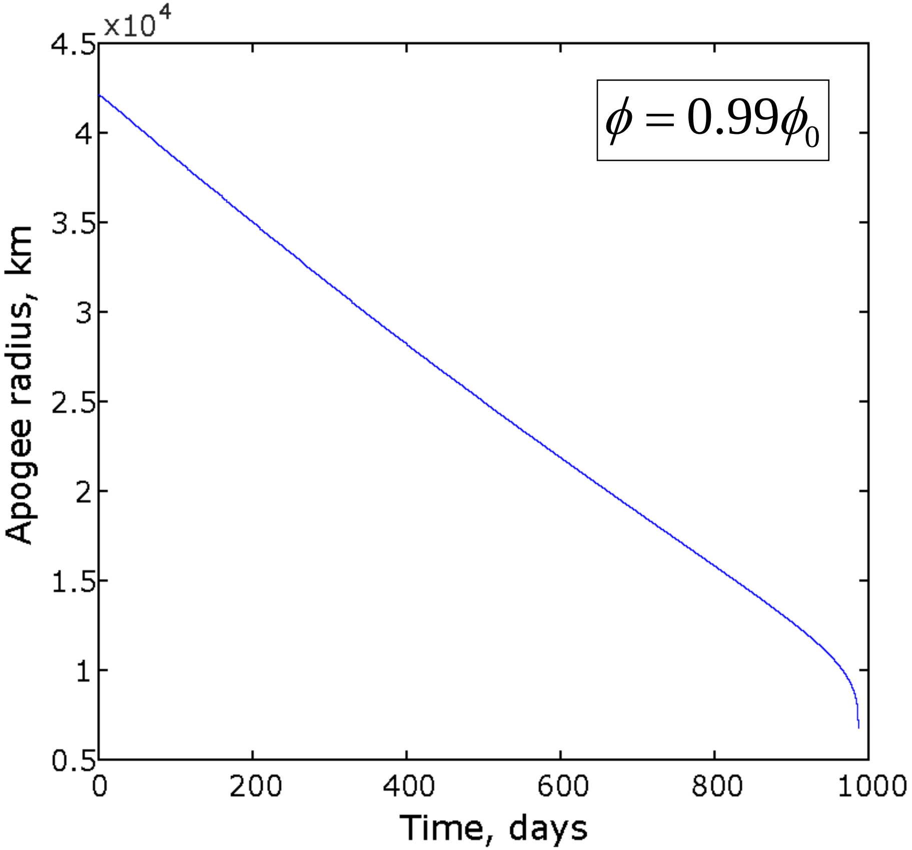
Single Case Analysis – part 1

Full deorbit simulation for a single system's configuration: $\boxed{\phi = 0.99\phi_0}$

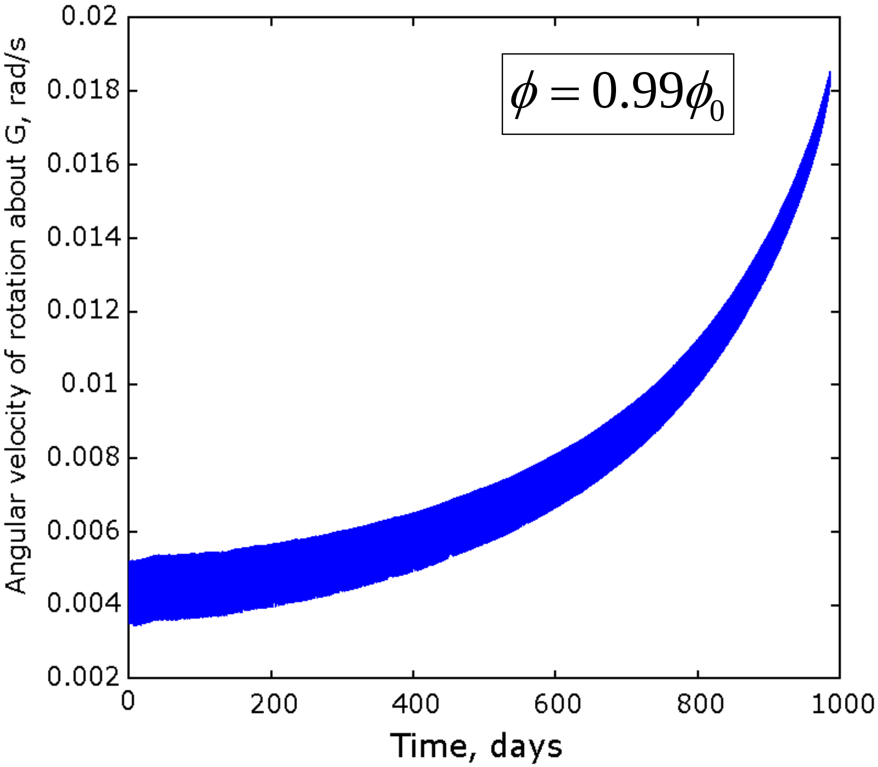
With $\phi < \phi_0$ the Lorentz torque during deorbit is positive, i.e. in the same direction as the orbital motion. A positive initial angular velocity must be provided to prevent initial slackness and instability. If $\phi > \phi_0$ the opposite applies.

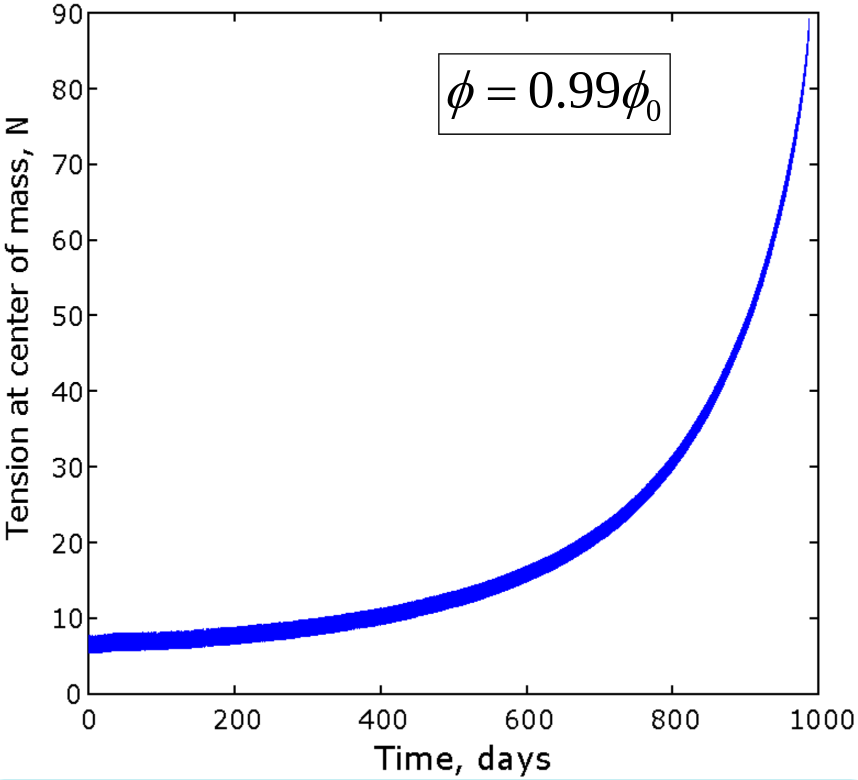
Eccentricity and apogee radius: constantly decreasing trend. Steep decrease in the last part, due to higher time spent at altitudes lower than 2000 km where perturbation drag forces are present.





Single Case Analysis – Part 2



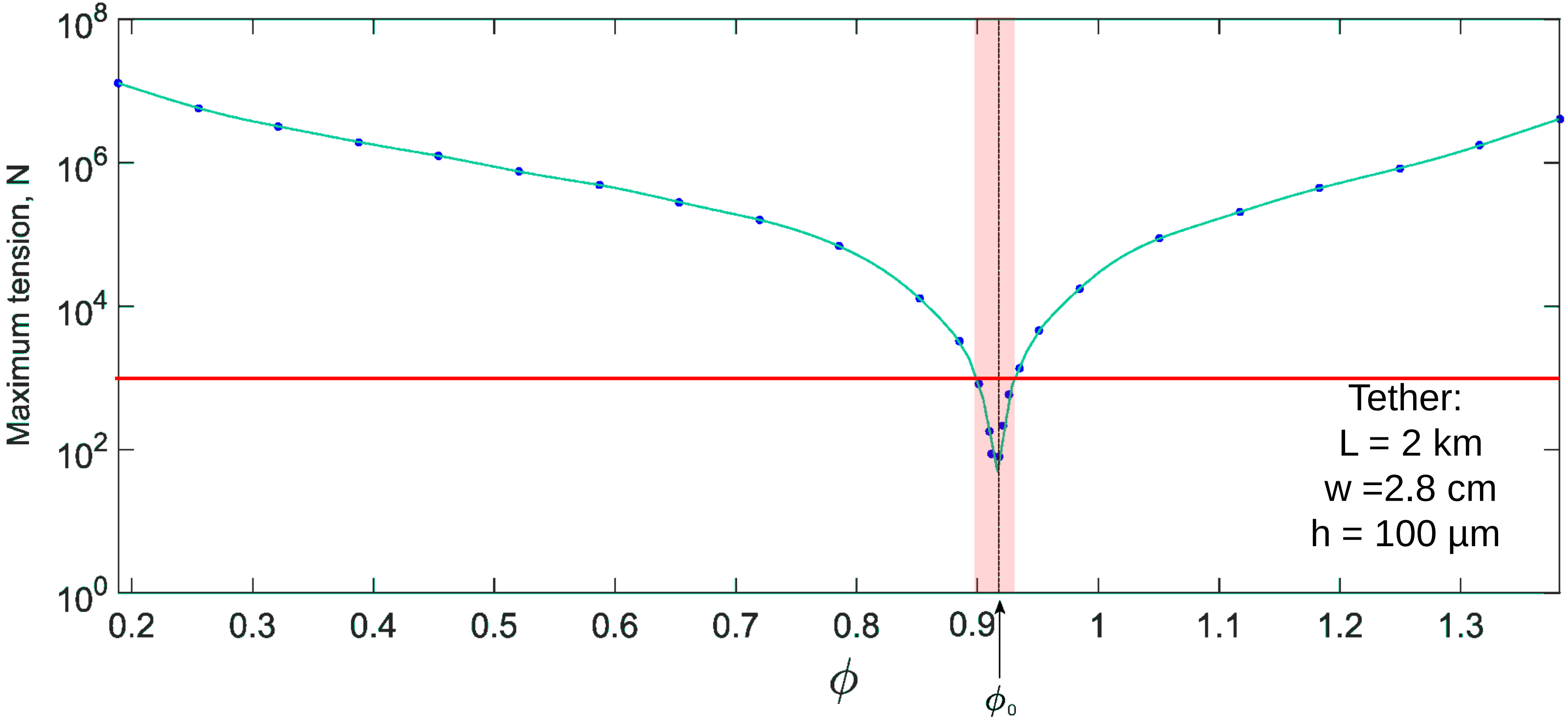


An initial angular velocity of + 0.004 rad/s is used to prevent tether slackness.
The angular velocity oscillates but is always positive, i.e. local rotation in same direction as orbital motion, and constantly increasing trend.

Tension is maximum at the system's center of mass. It is mainly due to centrifugal force generated by local rotation. Oscillating behavior, always positive, constantly increasing trend. **Maximum tension of about 88 N**. Even with Al 1100 full deorbit is possible, far from breaking (and safety fac.= 3).

Deorbit time of 987 days, i.e. **2.7 years**: much lower than natural decay time that is higher than 25 years (with 90% confidence; computed with *Stela*, courtesy of *Centre National d'Études Spatiales*)

Multiple case analysis



27 full deorbit simulations are run to obtain the maximum tension at center of mass during the entire deorbit, each for a different value of phi, from $\phi_{\min} = \arcsin(\Lambda_t / 2)$ to $\phi_{\max} = \arccos(\Lambda_t / 2)$

Knowing the tether material, the user can determine the allowed range of ϕ to avoid tether breaking. E.g. using a Metal Matrix composite with Aluminum matrix and reinforcing fibers of Nextel it is possible to reach an UTS of 1450 Mpa, and **maximum allowed tension, with safety factor K = 3, of 1750 N** leading to a **range of ϕ between 0.89 and 0.94 (center of mass between 700 and 790 m from cathodic tip).**

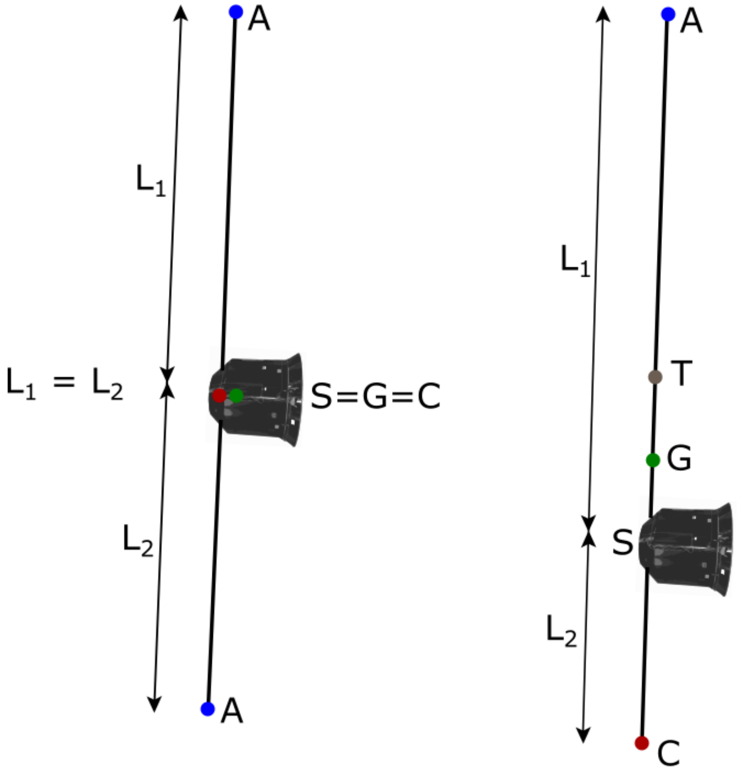
Double Bare-Electrodynamic-Tether (*BET*) or “butterfly” configuration

Two separate BETs of equal length: One/Two cathodes required

- Redundancy
- Symmetrical configuration both before and after deployment (G coincident with Sylda)
- Higher performance (current is always generated throughout the rotation)

One single BET deployed twoways with different lengths on each side. Only one cathode required.

- Advantage of mass (only one cathode), and capability of having eletrodynamic center of mass as close as possible to center of mass of the system.
- Lower performance (during part of the rotation no current is generated).
- More challenging storage: need of splitting the mass in two parts placed axialsymmetrically.



A: anode
G: center of mass of the system
C: cathode
S: object to deorbit
T: tether's center of mass

What’s next?

Implementation of out-of-plane dynamics & additional gravitational perturbations

↓

Numerical implementation and analysis of double tether, or *butterfly* configuration, in GTO deorbit

↓

Preliminary analysis of deployment strategy and conceptual design of deployment system

↓

Attitude detection system
Study and design of *stereo vision system*
for tether’s attitude detection from 3D sensing

↓

Optimization
Progressive refinement of system’s design and computational code, with the objectives of minimum mass, and to ensure tether attitude stability over time and no breaking during deorbit