Bare Photovoltaic Tether Characteristics for ISS reboost

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Outline

1. International Space Station

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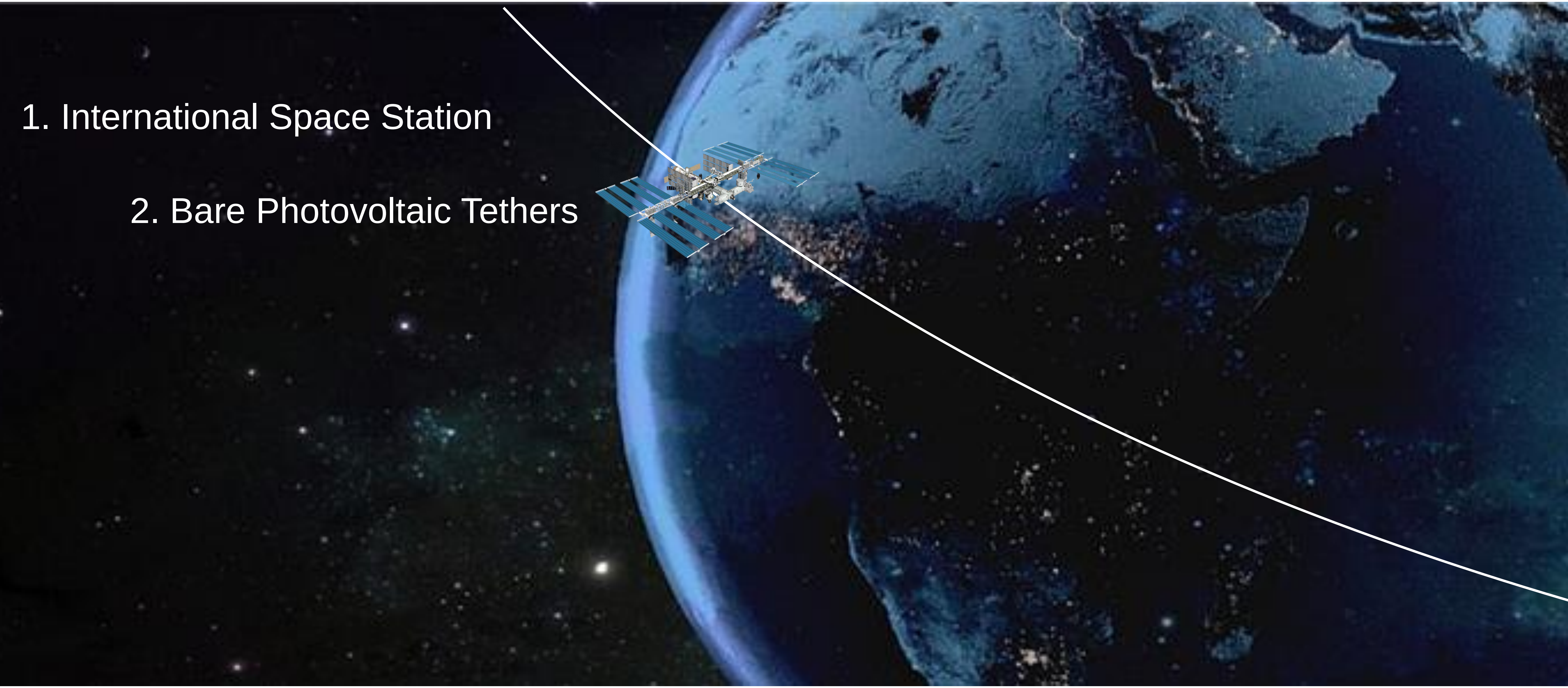

1. International Space Station
2. Bare Photovoltaic Tethers

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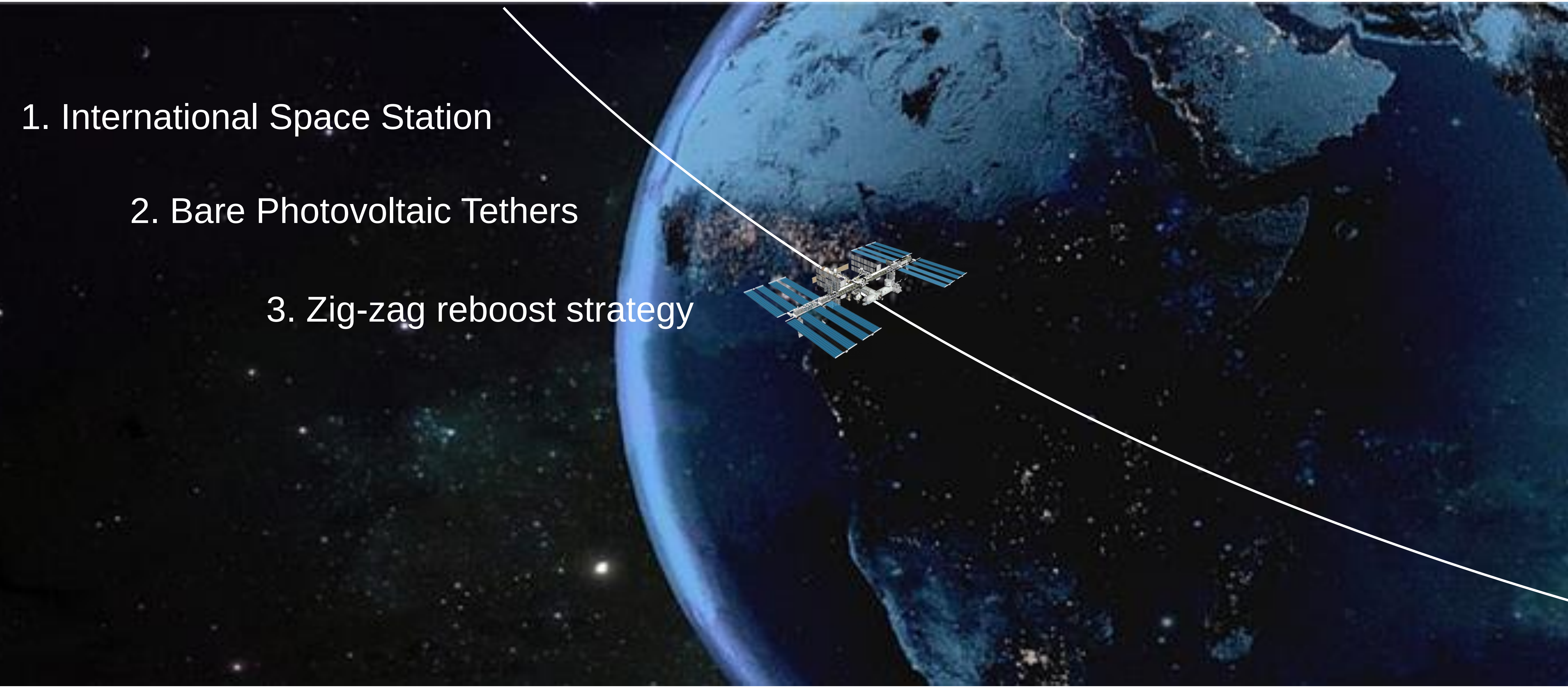

1. International Space Station

2. Bare Photovoltaic Tethers

3. Zig-zag reboost strategy

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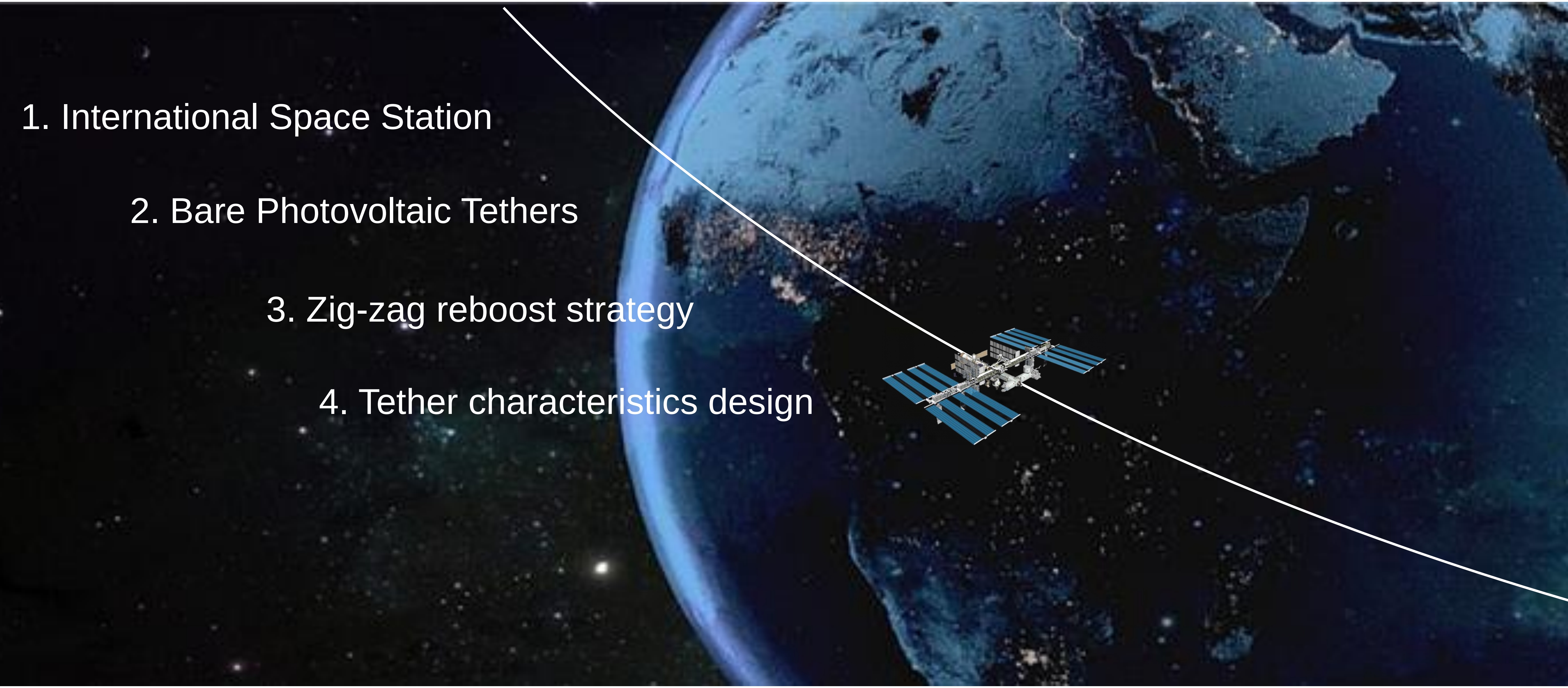

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4. Tether characteristics design

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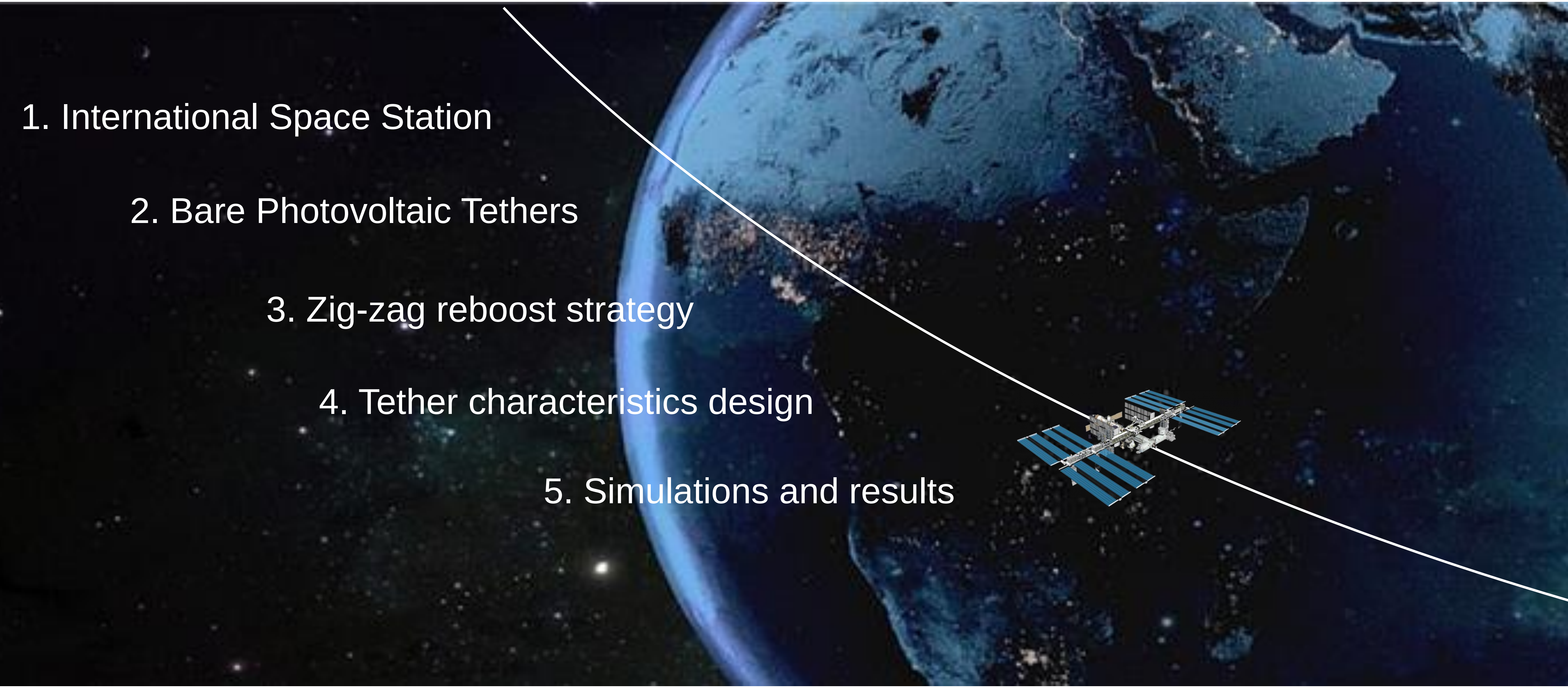

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5. Simulations and results

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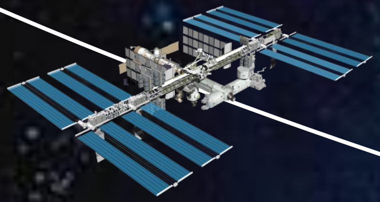
6. Conclusions

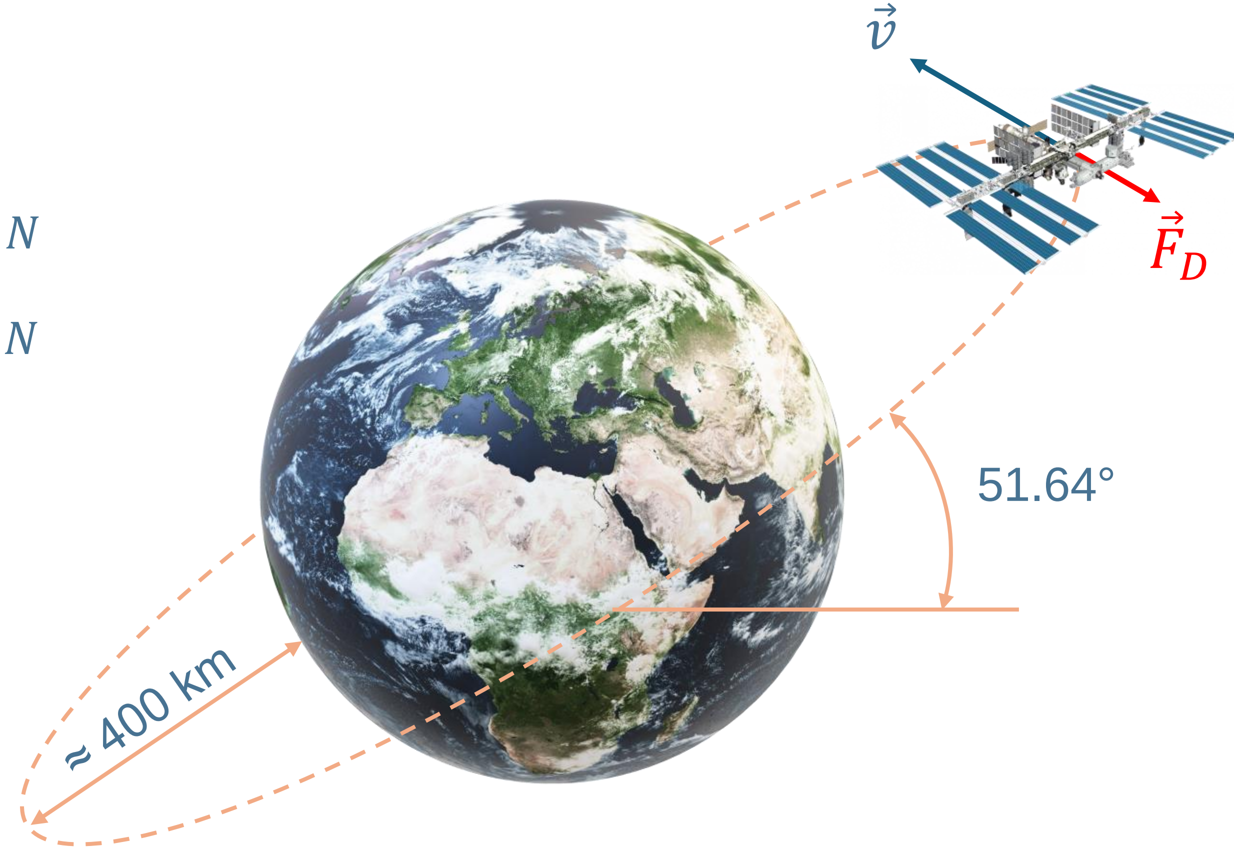


International Space Station

- Orbit inclination of $\approx 51.64°$
- Low Earth Orbit (LEO), altitude of $\approx 400\ km$

Aerodynamic drag
- $F_D = 1.1\ N$
- $F_D = 0.2\ N$

Natural decay
- $35 \pm 6\ km/year$ $(2.95\ km/month)$
- $13 \pm 5\ km/year$ $(1.08\ km/month)$



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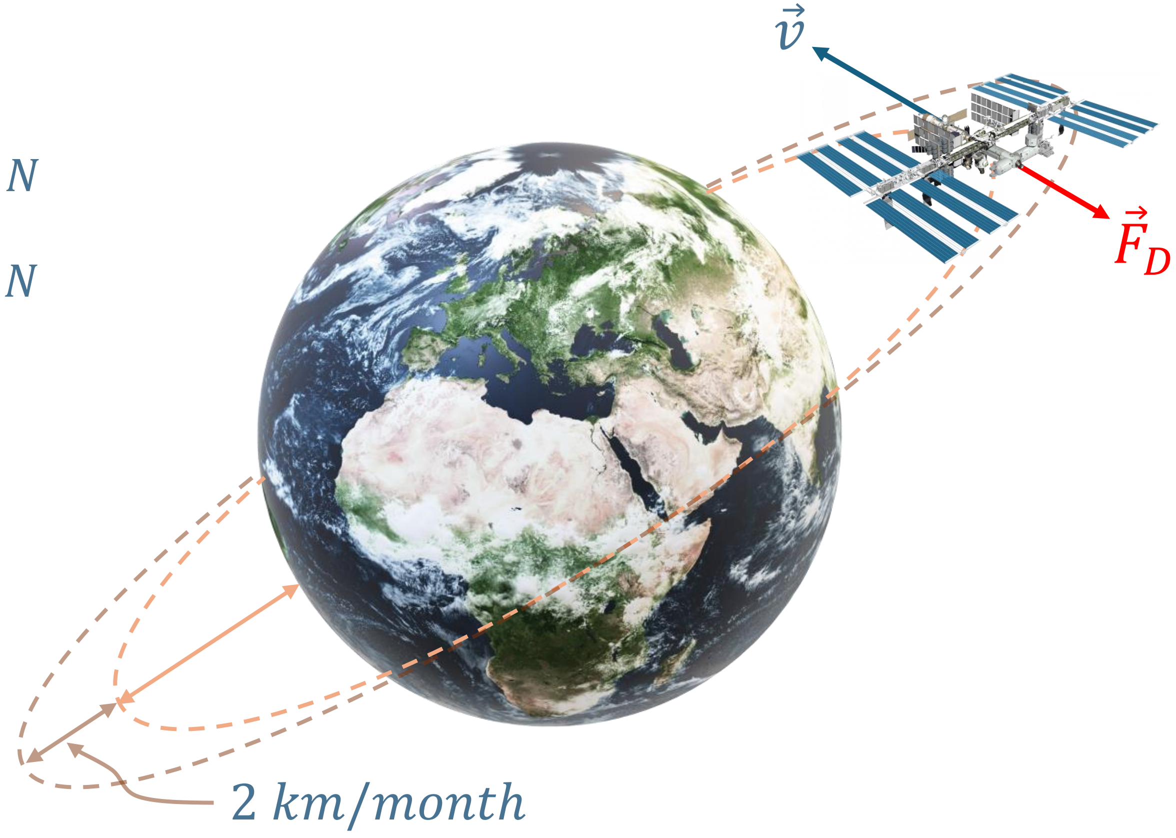
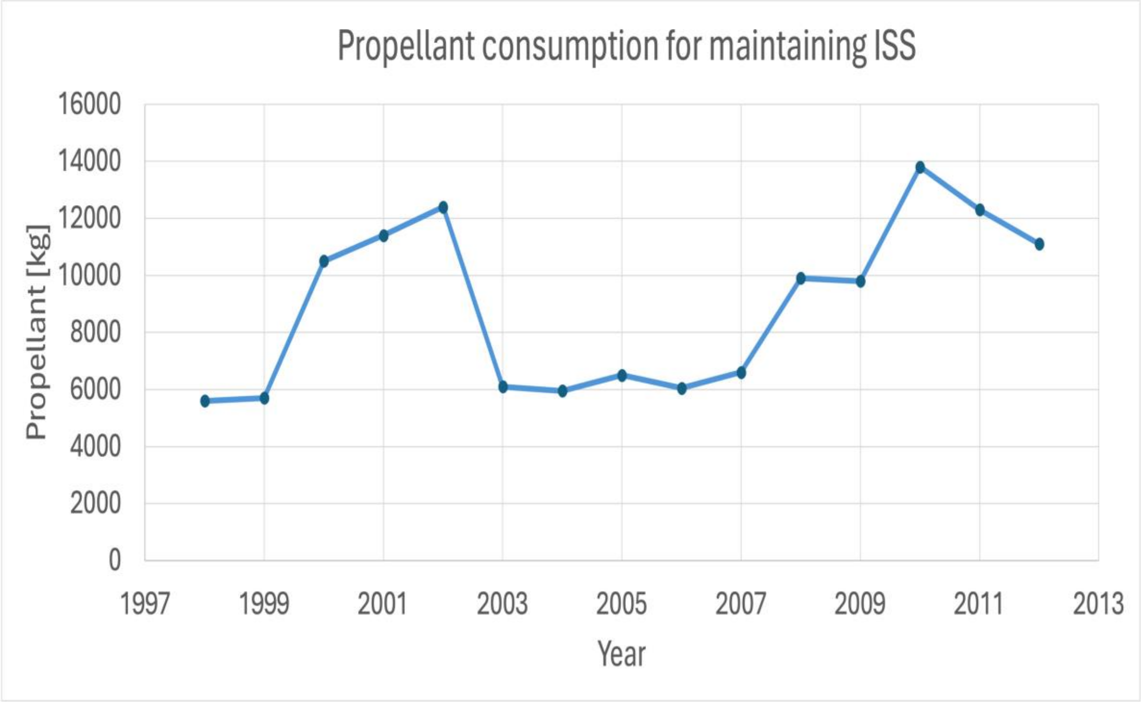
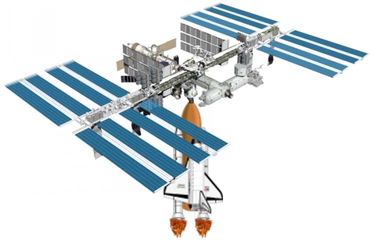


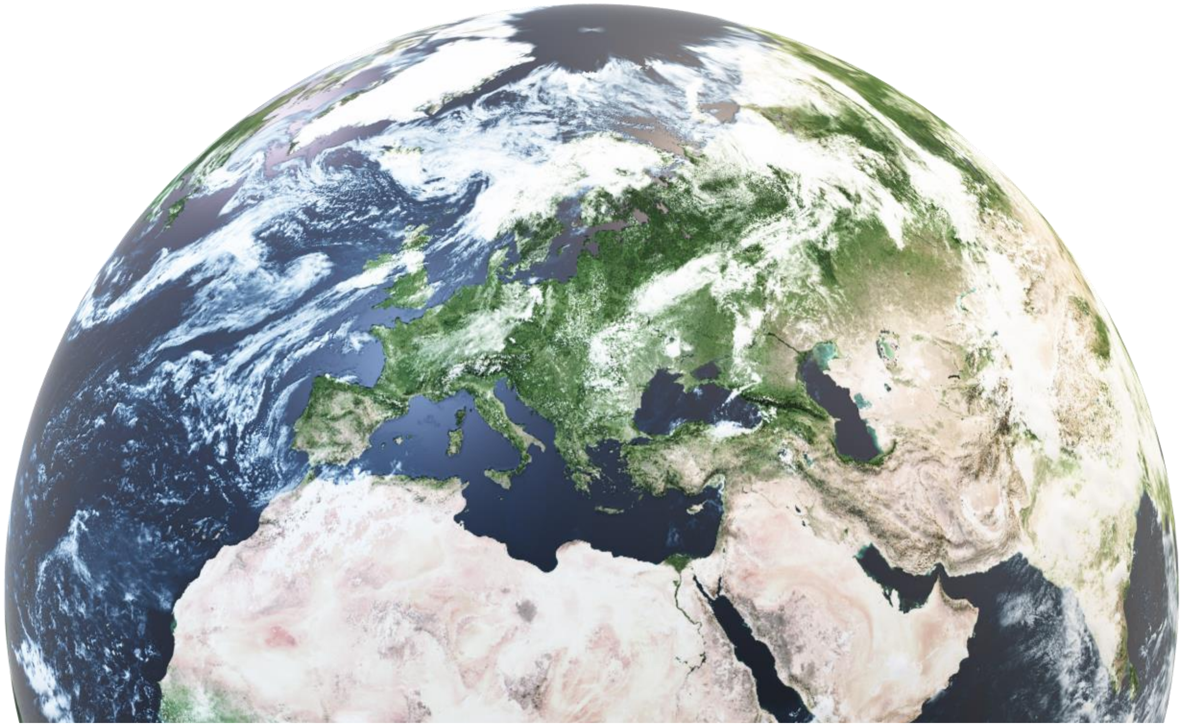
International Space Station

Reboost maneuvers are required periodically.

Several tons of propellant are used.

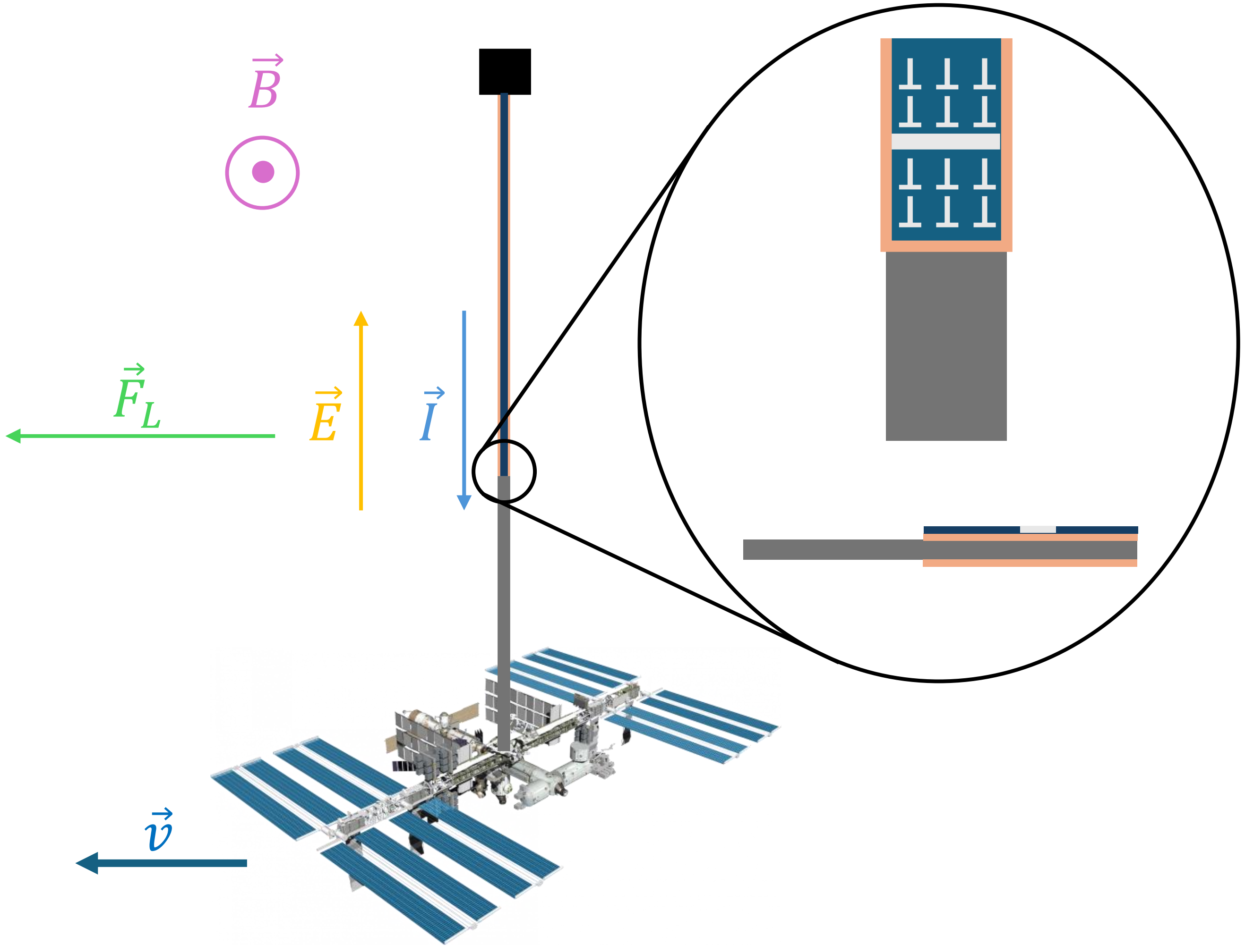




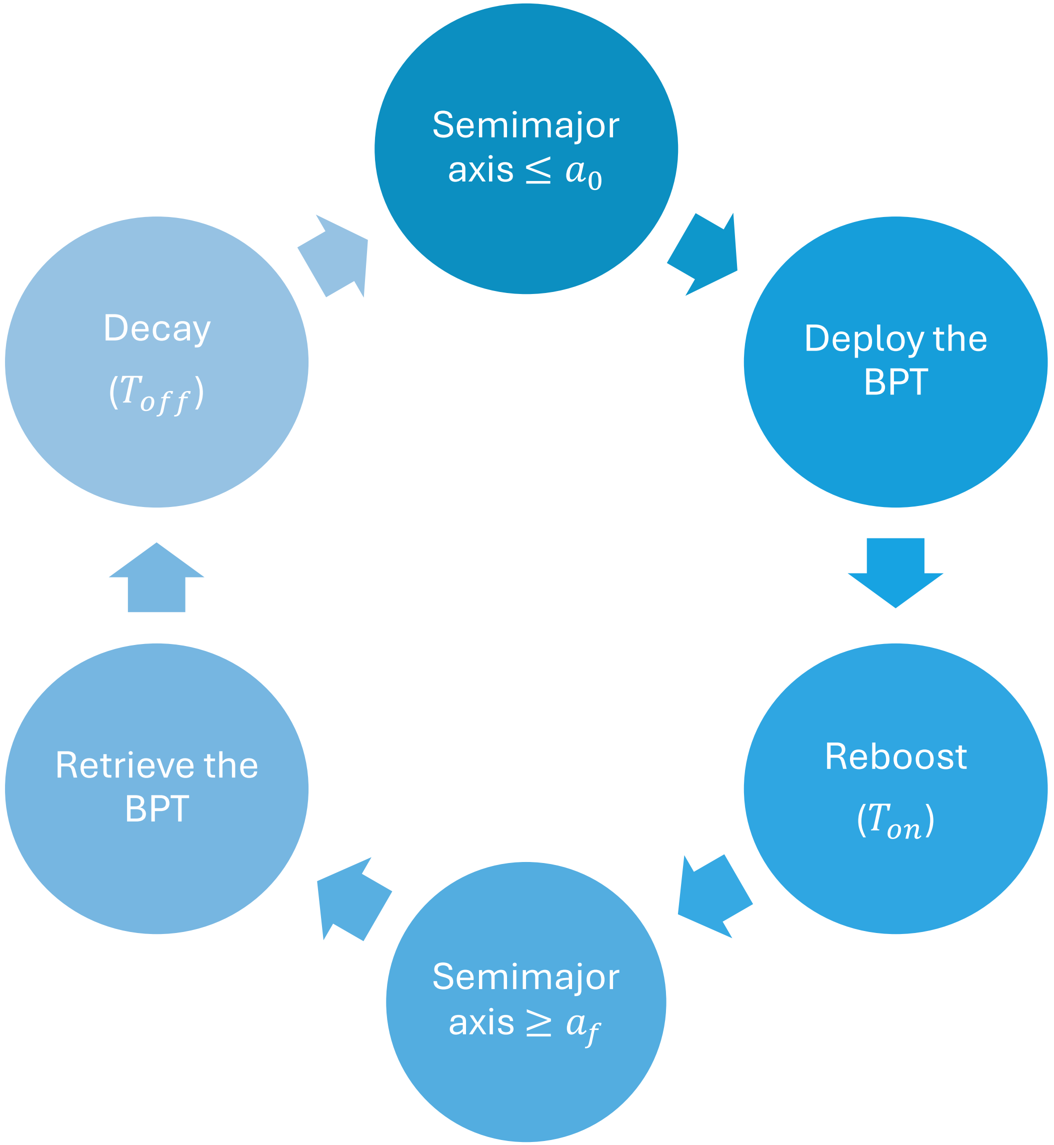


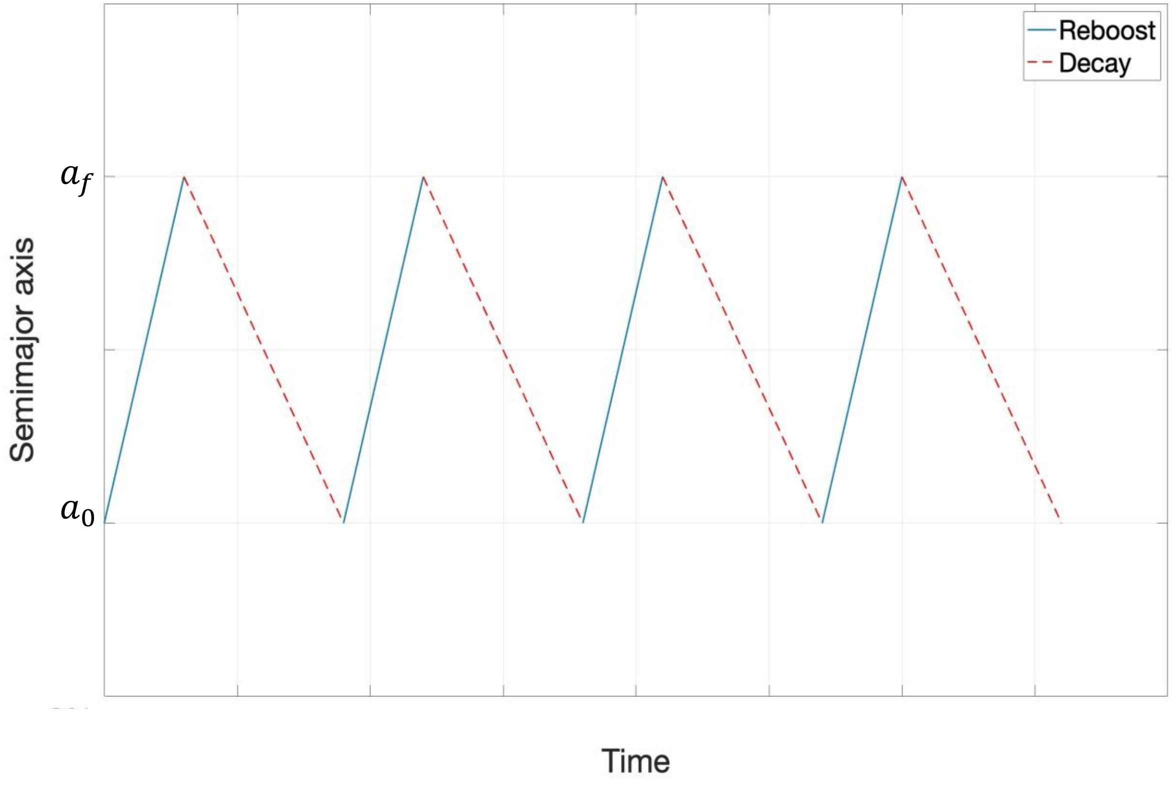
Bare Photovoltaic Tethers (BPTs)

- Electro dynamic tether (EDT) architecture
- Thin film of solar cells
- Solar cells harvest power when illuminated by solar rays
  - Fully autonomous system
- Upward deployment
  - Satisfies the $\boldsymbol{E} \cdot \boldsymbol{I} < 0$ condition (active mode)
  - Avoids the approaching corridors



Zig-zag control strategy





Zig-zag control strategy

$$\ddot{\boldsymbol{r}} = -\frac{\mu}{r^3}\boldsymbol{r} + \frac{\boldsymbol{F}}{m_{ISS}}$$

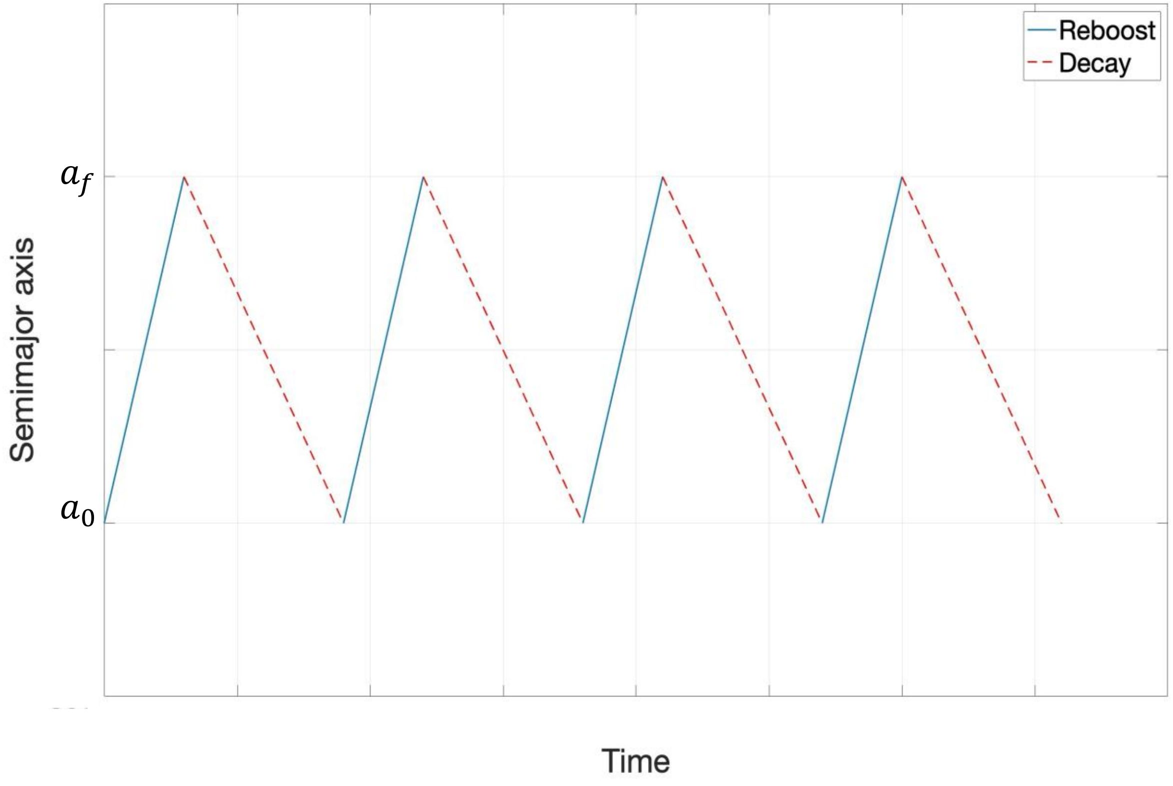
- Small eccentricity
- F_D, F_L and v are assumed not varying with a

$$T_{on} - \frac{\mu m_{ISS}}{2(\boldsymbol{F}_L - \boldsymbol{F}_D)\cdot \boldsymbol{v}} \frac{a_f - a_0}{a_0 a_f} = 0$$

$$\tau_{on} - \frac{1}{2\left(\xi_t\, i_{av} - \widetilde{W}_D\right)} \frac{a_f - a_0}{a_f} = 0$$

Goal: find η_{pv} for different tether geometries (L_{bare}, L_{pv}) and aerodynamic drag forces.

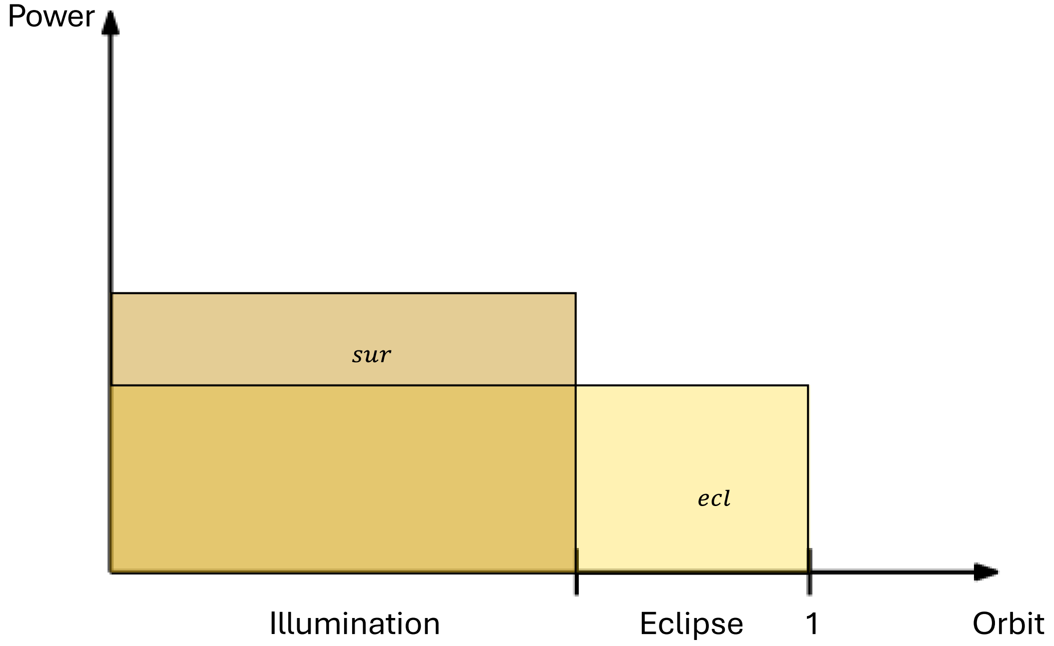
$$\eta_{pv,k+1} = \eta_{pv,k} - \frac{g(\eta_{pv,k})}{g'(\eta_{pv,k})}$$



During solar illumation a higher power must be harvested by the cells.

Higher cells efficiency and batteries to store the power are required.

$$f_{ecl} = \frac{W_{orbit}}{W_{illumination}} = \frac{t_{orbit}}{t_{illumination}}$$



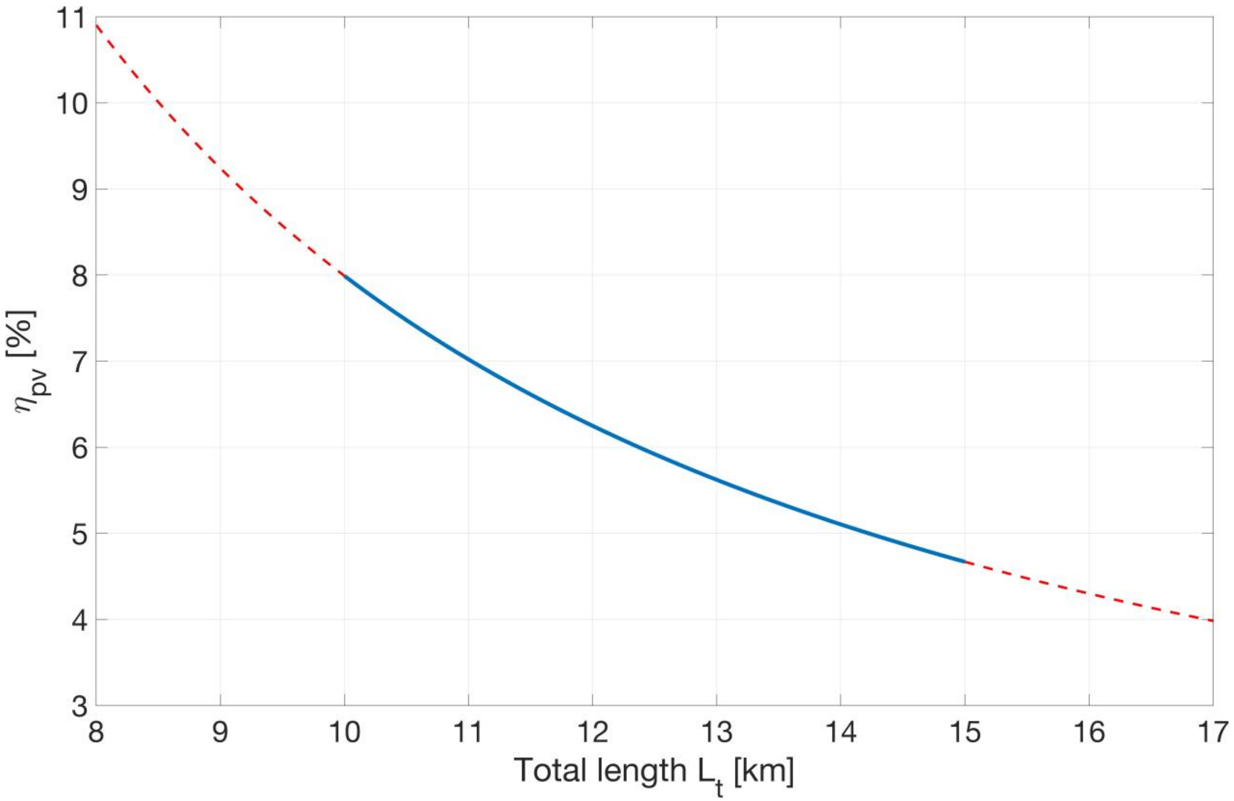
Tether characteristics

Parameters	Value
m_{ISS}	$450000\ kg$
A_{ISS}	$1670\ \ m^2$
C_D	2.2
w_t	$50\ mm$
t_t	$50\ \mu m$
σ_t	$3.55 \cdot 10^7 (\Omega m)^{-1}$
V_C	$-30\ V$
E_m	$0.12\ \ V/m$
N_0	$5.90 \cdot 10^{11}\ \ m^{-3}$
T_{on}	$30\ days$
F_D	$0.4 \div 0.8\ N$
a_0	$400\ km$
a_f	$404\ km$

Tether characteristics

L_t [km]	f_i [%]	L_{pv} [km]	η_{pv} [%]
10.00	90	9.00	7.99
10.50	90	9.45	7.48
11.00	90	9.90	7.02
11.50	90	10.35	6.61
12.00	90	10.80	6.25
12.50	90	11.25	5.92
13.00	90	11.70	5.62
13.50	90	12.15	5.35
14.00	90	12.60	5.10
14.50	90	13.05	4.88
15.00	90	13.50	4.67

$F_D = 0.4\ N$



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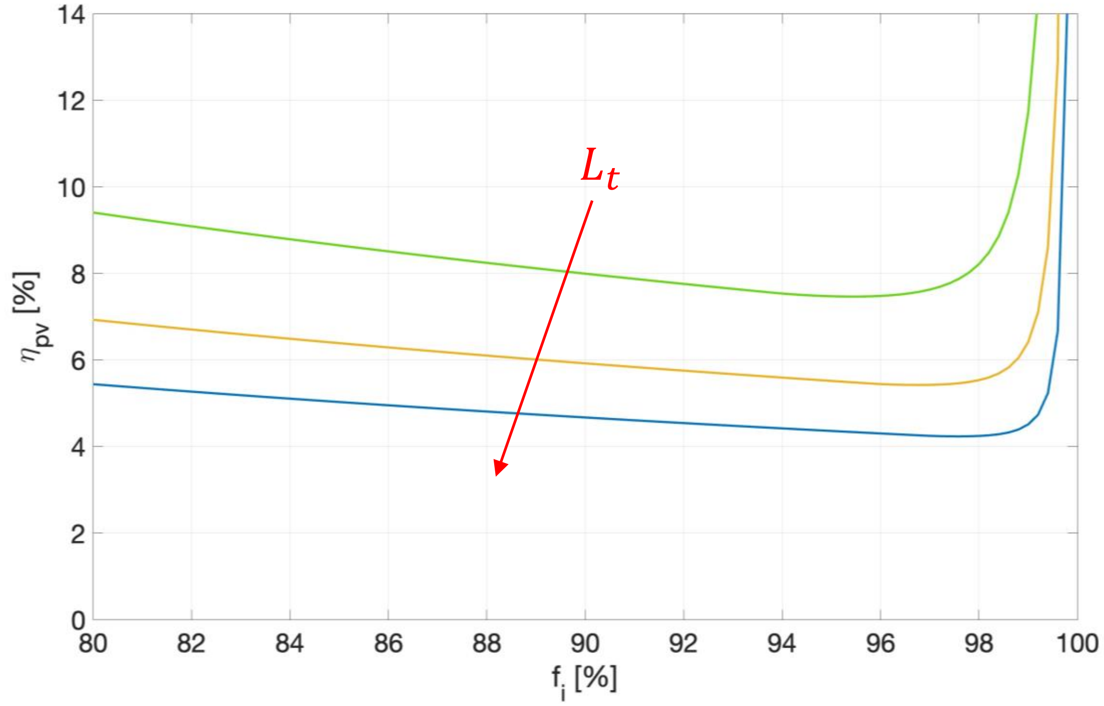
12.50	90	11.25	5.92
13.00	90	11.70	5.62
13.50	90	12.15	5.35
14.00	90	12.60	5.10
14.50	90	13.05	4.88
15.00	90	13.50	4.67

$F_D = 0.4\ N$

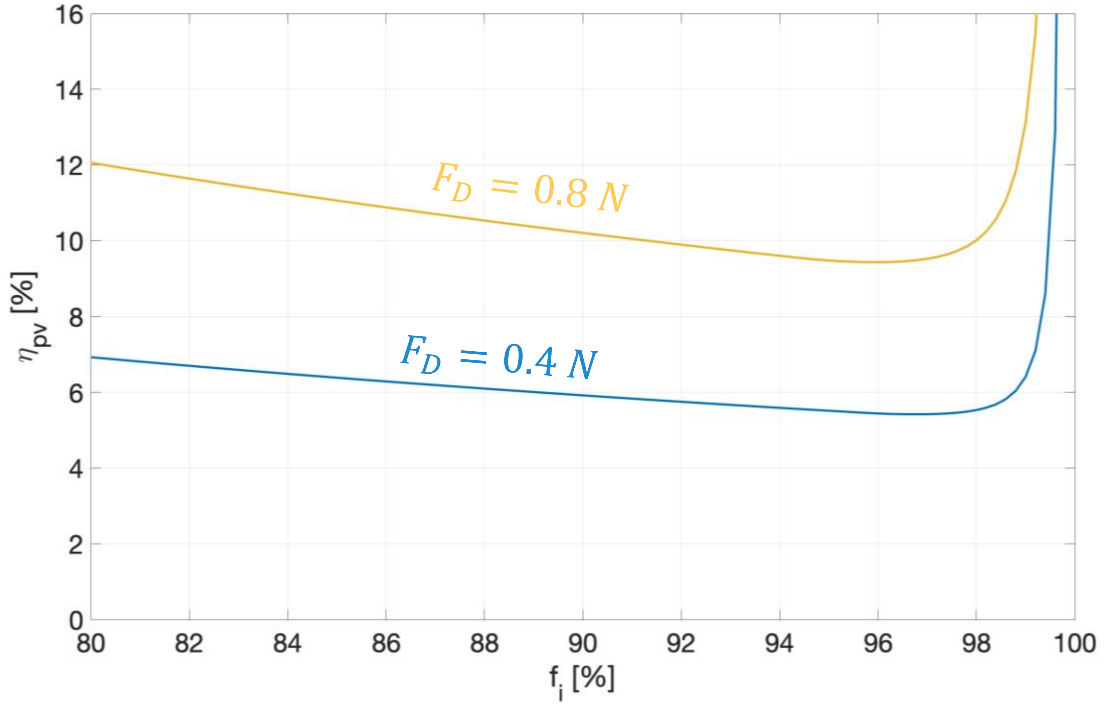
L_t [km]	f_i [%]	L_{pv} [km]	η_{pv} [%]
10.00	90	9.00	14.04
10.50	90	9.45	12.23
11.00	90	9.90	10.81
11.50	90	10.35	9.66
12.00	90	10.80	8.72
12.50	90	11.25	7.93
13.00	90	11.70	7.27
13.50	90	12.15	6.70
14.00	90	12.60	6.21
14.50	90	13.05	5.78
15.00	90	13.50	5.41

$F_D = 0.8\ N$

Tether characteristics



$F_D = 0.4\ N$
$L_t = 10, 12.5, 15\ km$



$F_D = 0.4$ and $0.8\ N$
$L_t = 12.5\ km$

Simulations

Outputs from previuos analysis must be validated. Thus they rae used as inputs for simulations performed using **FLEXSIM**.

- a software fully developed at the University of Padua for the E.T.PACK project initiative.

- allows to simulate both deorbiting and reboost missions with electrodynamic and bare photovoltaic tethers.

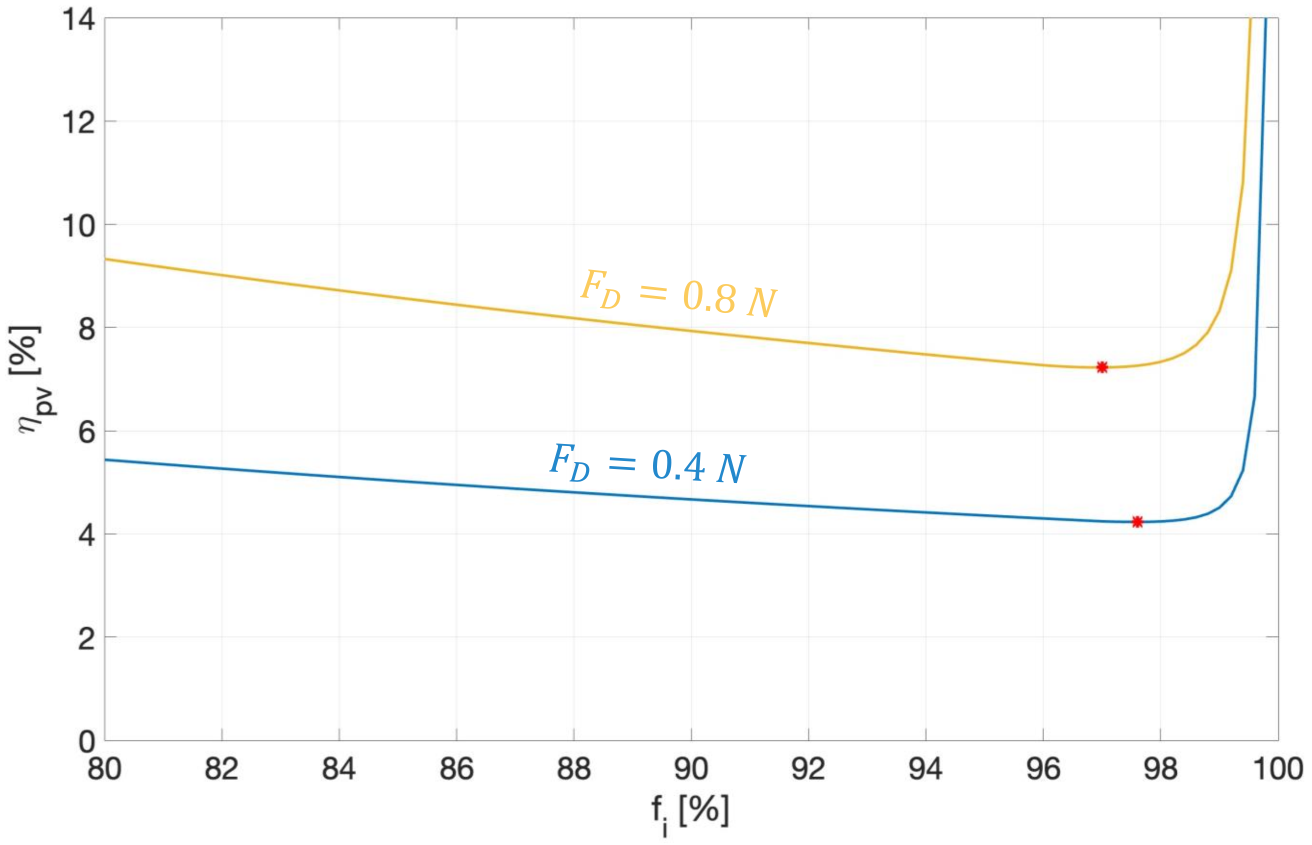
Models adopted:

- Spherical gravitational model
- NRLMSISE–00 for the the atmosphere
- IGRF for the geomagnetic field
- IRI for the ionosphere

Tether is assumed to be always aligned with the local vertical.

Simulations

	$F_D = 0.4\ N$	$F_D = 0.8\ N$
L_t	15.00 km	15.00 km
f_i	97.6%	97.0%
L_{pv}	14.64 km	14.45 km
η_{pv}	4.23 %	7.23 %



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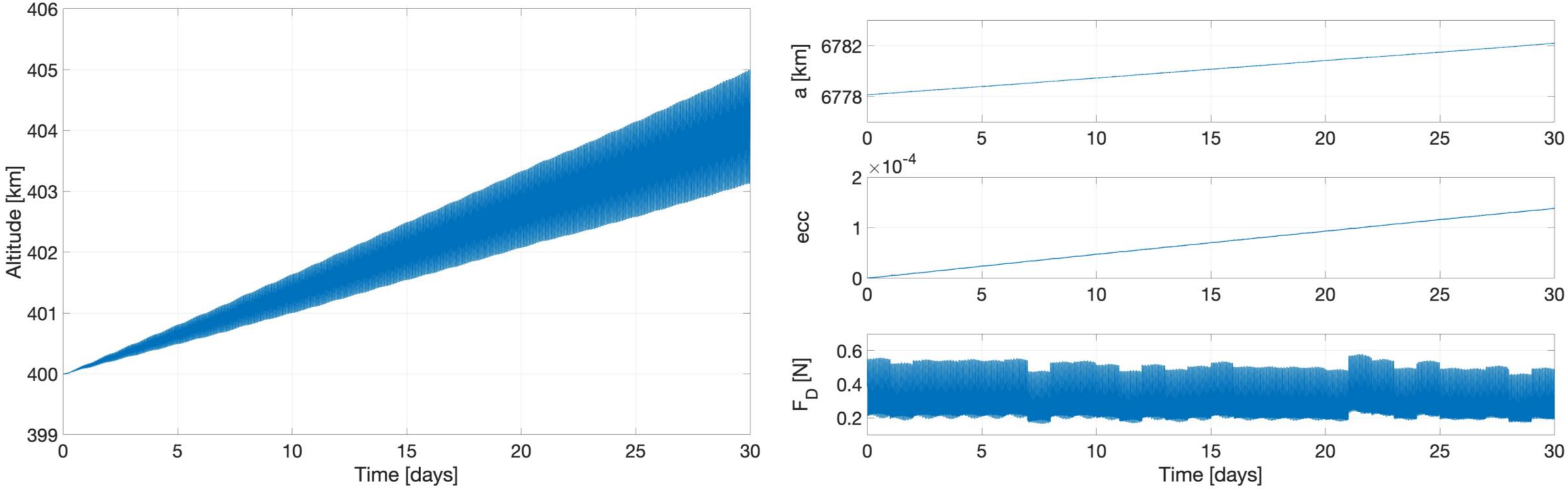
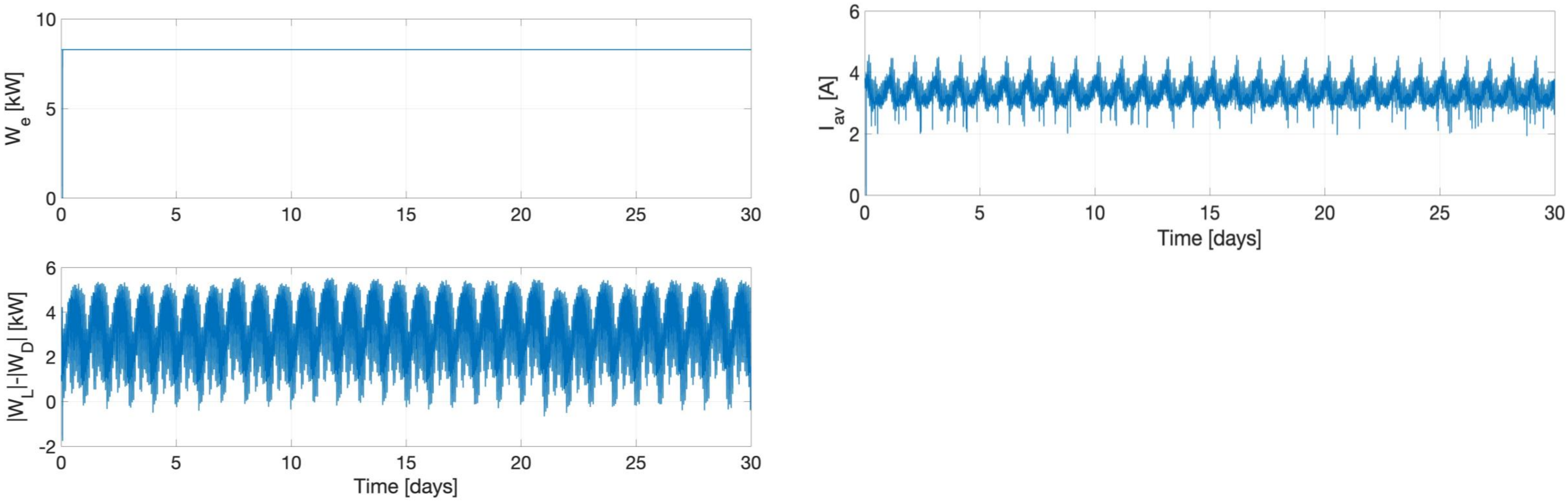


Simulation starting date is March 1st, 2003

Simulations



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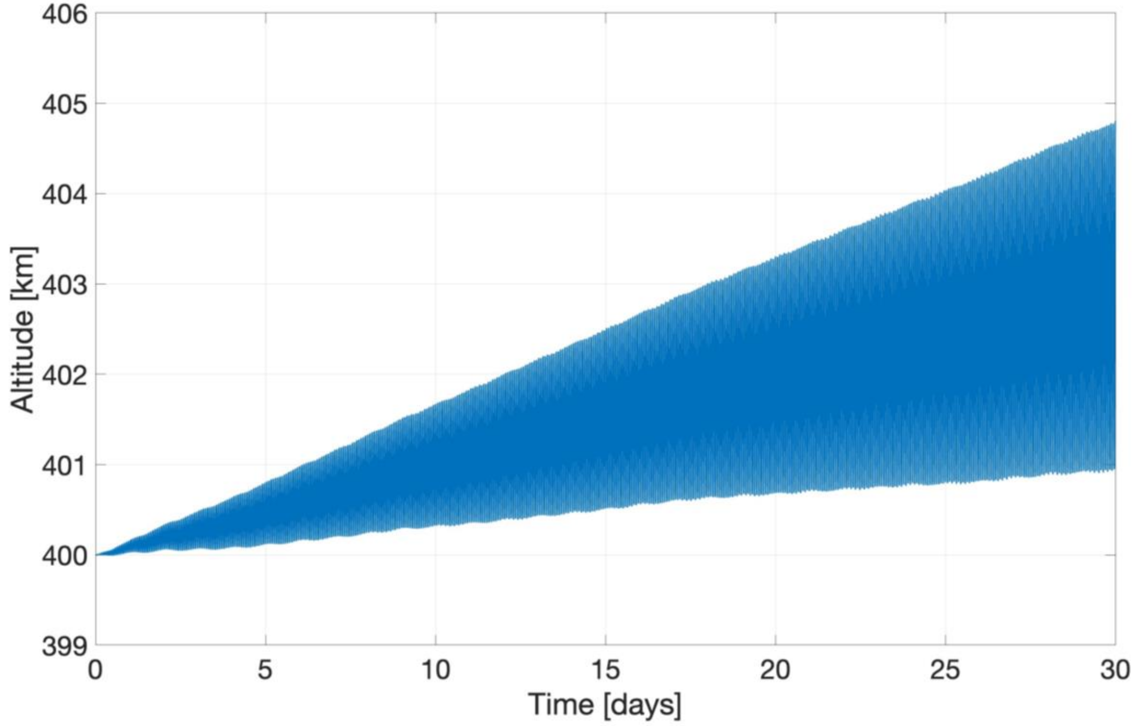
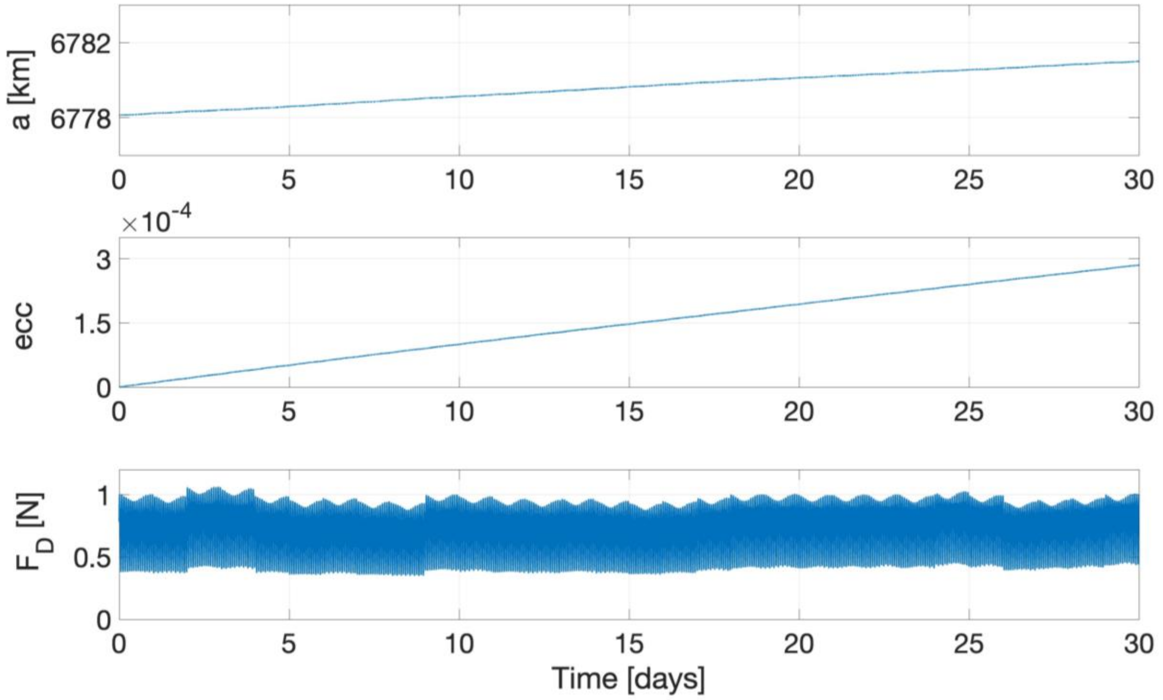
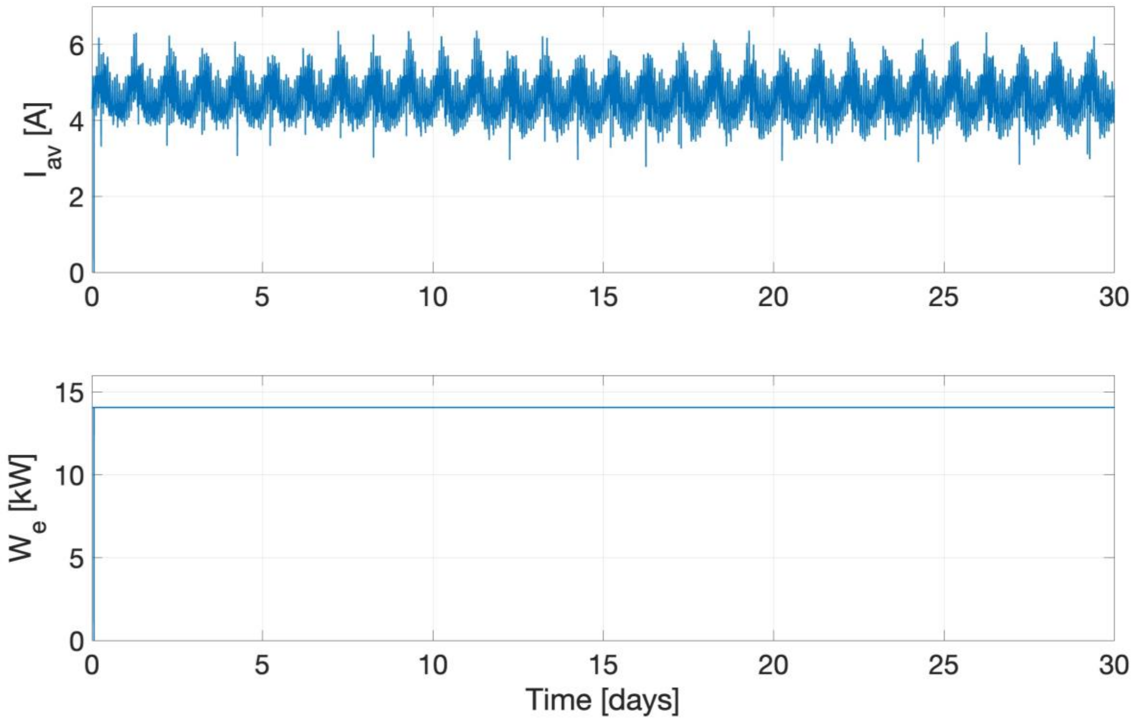
Simulations

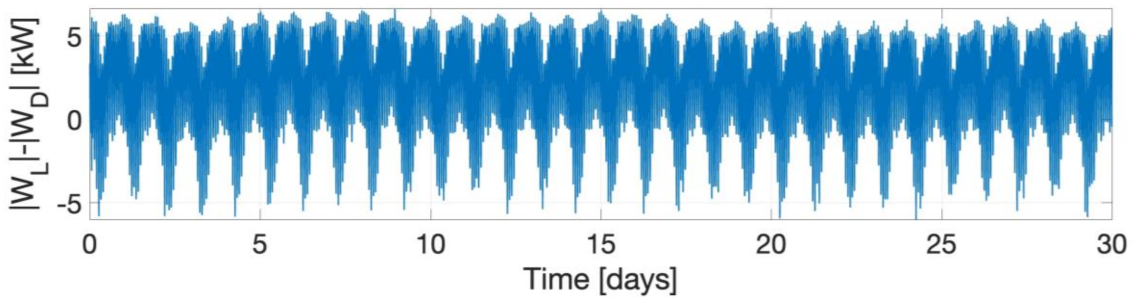




Simulation starting date is December 1st, 2001

Simulations





Simulation starting date is December 1st, 2001

Conclusions

- BPT is a promising technology for the reboost of the ISS

- BPT is a fully autonomous system

- A preliminary design model was analyzed. Since the BPT should be capable of functioning effectively for several years, two options are proposed:
    a) employing the most efficient BPT, specifically designed for the upper drag threshold
    b) opting for a design tailored for an average drag of 0.6 N or 0.7 N

- Future investigations should be done on the stability simulating a flexible tether.

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THANK YOU FOR THE ATTENTION!

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