Control of the Rotating Tethered System for Orbital Debris Removal

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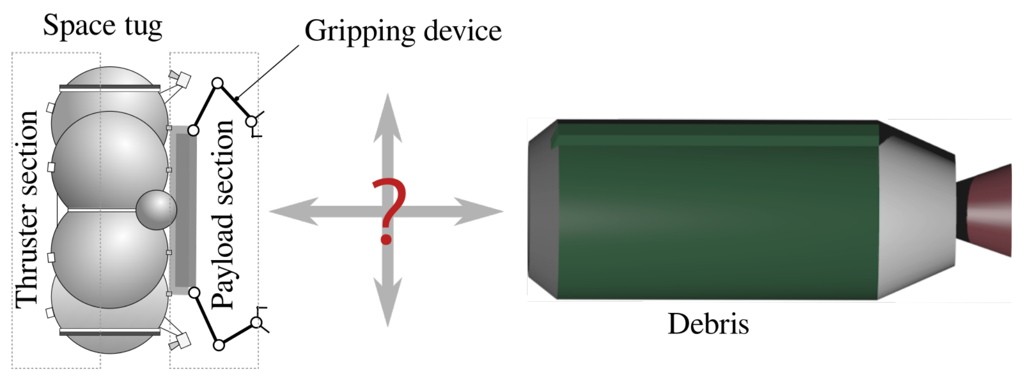
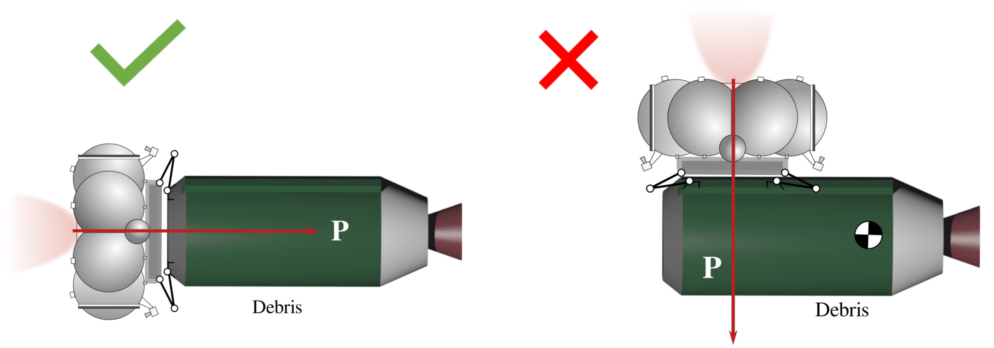
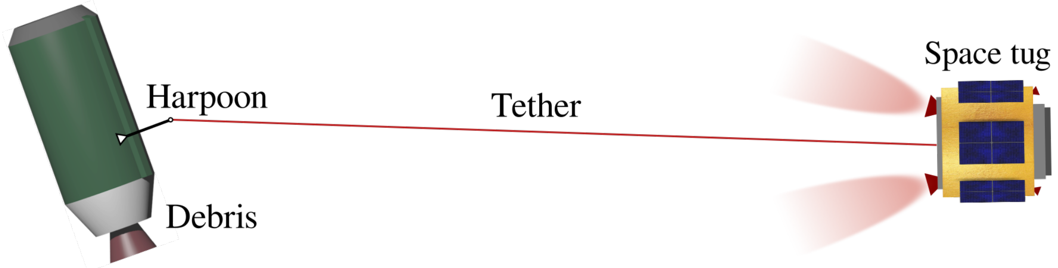
Contact ADR methods & existing orbital stages







Methods that require rigid contact between the space tug and debris

- The upper stage (space tug) is required to perform unusual rendezvous and docking tasks
- Thrust arm relative to the tug-debris system center of mass should be close to zero (but some debris objects are asymmetric)

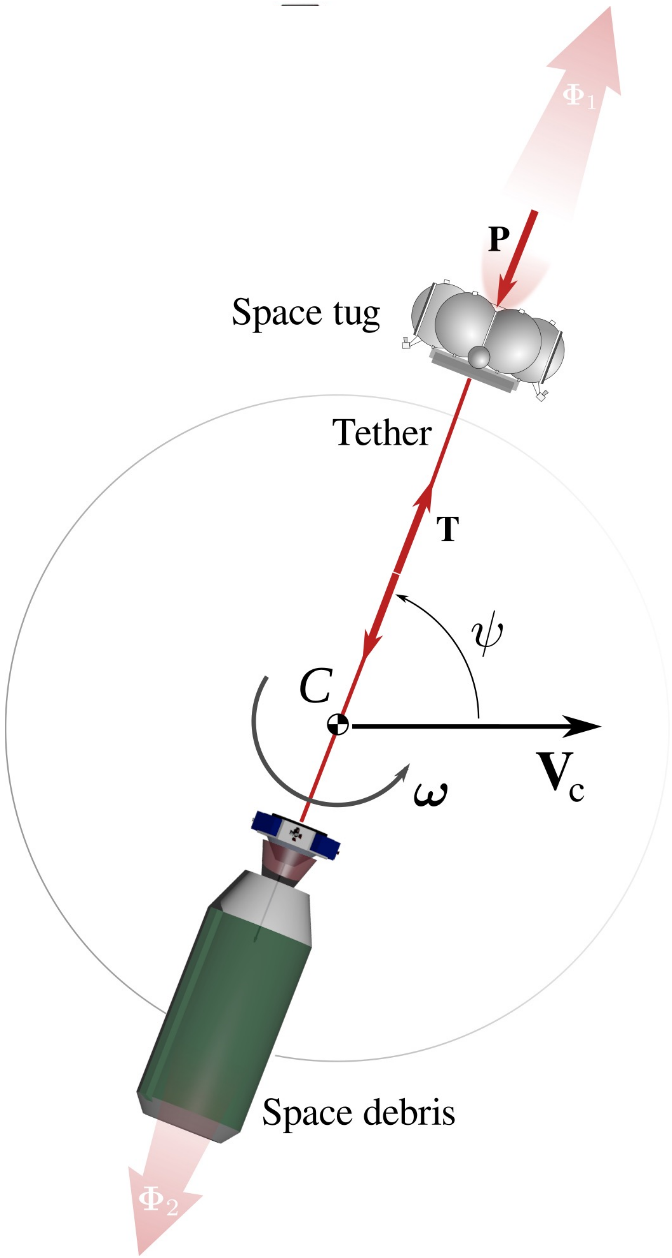
Tethered towing (<u>pull</u> towing)

- Tether control device should be at the rear part of the space tug, where the thruster is installed
- Thruster exhaust plume could damage the tether

Autonomous docking module

- ADR specific tasks could be delegated to **A**utonomous **D**ocking **M**odule
- **ADM** is a small spacecraft that carries all specific equipment for ADR mission
  - Gripping device
  - Maneuvering thrusters
  - Cameras, LiDARs
- **ADM should have ability to dock with the space tug** (the tether could assist in the ADM-Tug docking process)
- Is it possible to use **push towing** scheme with the tethered space tug and debris?

Rotating tethered system



Rotation of TSS induces the tension $\boldsymbol{l} - l_0$ in the tether of free length $\boldsymbol{l}_0$. Tether tension force is

$$T = m_{12}\omega^2\boldsymbol{l}$$

Tug's thrust P can be applied along the tether

$$P < T,$$

The space tug could **push** the debris object through the tether, so the conventional upper stages could be used as space tugs for **tethered towing**

For example:

- Tether length: **2 km**
- Masses m_{deb} = **3000** kg, m_{tug} = **1700** kg
- $m_{12} = m_{tug}m_{deb}/(m_{tug} + m_{deb}) = 1085$ kg
- $\omega =$ **2** deg/s, T = **2.6** kN.

Problem

*Rotation of the tether is not shown

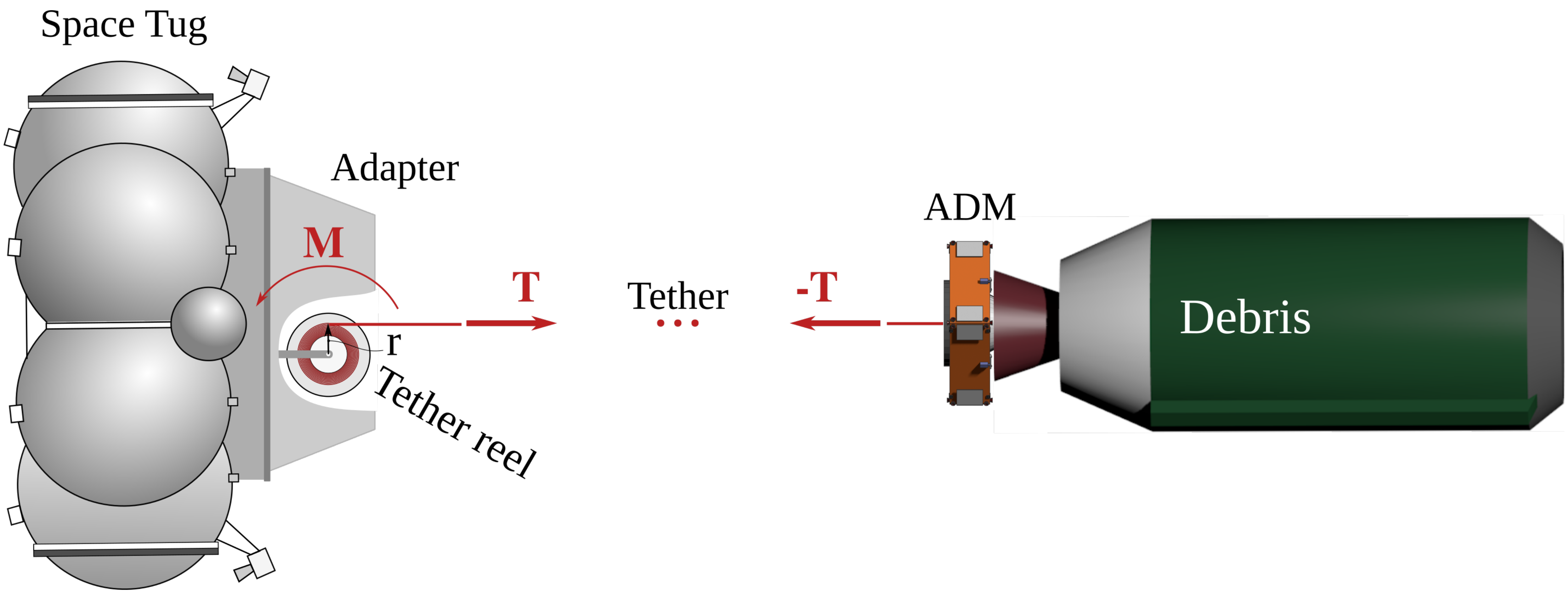
- How to control of the tether tension after the gripping?
- How to control of the tether tension upon thruster's switching on and off?

Control techniques:

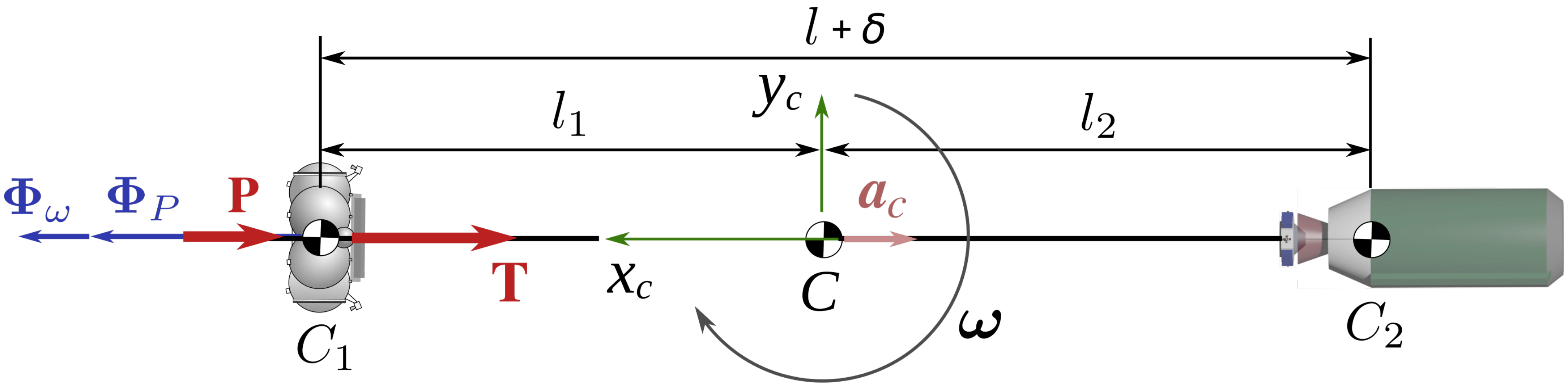
- Tug's thrust[1]
- Control of the free length of the tether

[1] Valeriy I. Trushlyakov and Vadim V. Yudintsev
Rotary Space Tether System for Active Debris Removal
Journal of Guidance, Control, and Dynamics 2020 43:2, 354-364

Tether reel

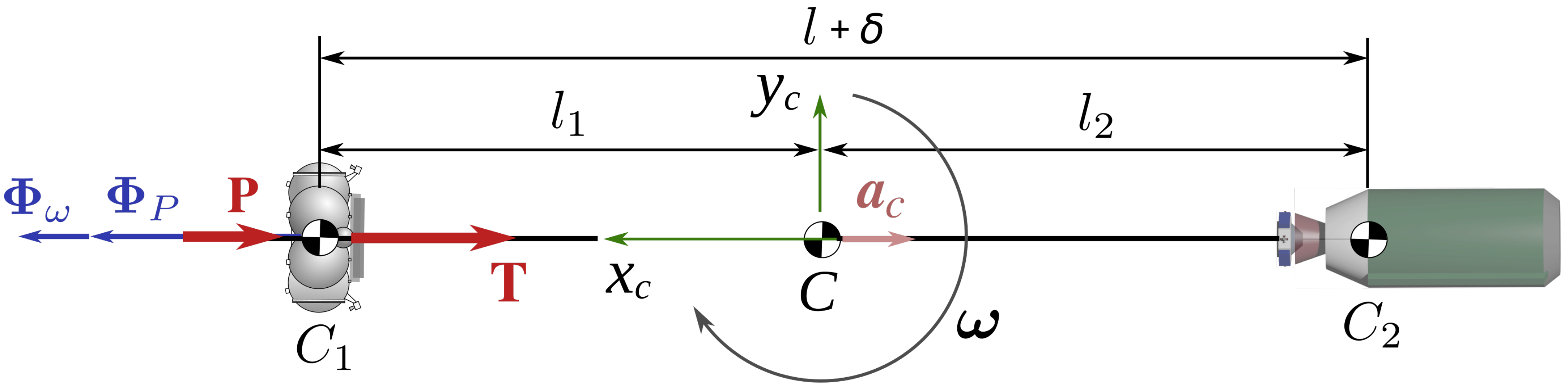


Assumptions



- The space tug and debris are point masses
- Angular rate of the tether is much greater than the orbital rate of the system and we neglect the effect of the Earth gravity to the tether rotation
- The tether is considered as a massless spring

Model



Space tug motion in Cx_cy_c frame along Cx_c

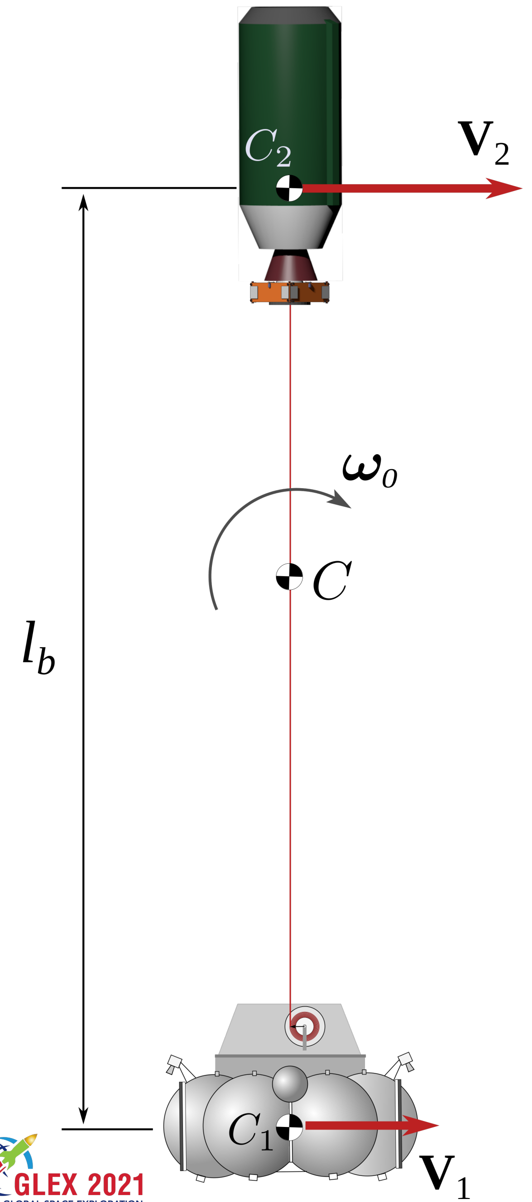
$$m_1\ddot{l}_1 = -T - P + \Phi_\omega + \Phi_P$$

where

$$\Phi_P = P\, m_1/(m_1 + m_2)\,, \qquad \Phi_\omega = m_1\omega^2 l_1, \qquad T = \frac{EA}{l}\delta$$

$$l_1 = (l+\delta)\frac{m_2}{m_1+m_2} = \frac{m_{12}}{m_1}(l+\delta), \qquad m_{12} = \frac{m_1 m_2}{m_1+m_2}$$

Equations



$$\ddot{l} + \ddot{\delta} = \omega_0^2 \frac{l_0^4}{(l+\delta)^3} - \frac{1}{m_{12}} \frac{EF}{l} \delta - \frac{P}{m_1}$$

Initial conditions:

$$l_0(0) = l_0, \qquad \dot{l}_0(0) = 0, \qquad \delta(0) = 0, \qquad \dot{\delta}(0) = 0, \qquad \omega_0 = \frac{V_2 - V_1}{l_0}$$

Stationary point:

$$l = l_0 = \text{const}, \qquad \delta = \delta_0 = \text{const}$$

δ_0 is obtained from the equation

$$\boxed{\frac{1}{m_{12}} \frac{EF}{l} \delta_0 = \omega_0^2 \frac{l_0^4}{(l_0 + \delta_0)^3} - \frac{P}{m_1}}$$

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Tether free length control

$$\ddot{l} + \ddot{\delta} = \omega_0^2 \frac{l_0^4}{(l+\delta)^3} - \frac{1}{m_{12}} \frac{EF}{l} \delta - \frac{P}{m_2}$$

Tether length

$$\boxed{\ddot{l} = \alpha_1 \dot{\delta} - \alpha_2 (l - l_0) - \alpha_3 \dot{l}}$$

$\alpha_1 \dot{\delta}$ term damps tether elastic oscillations

$\alpha_2 (l - l_0)$ term restores the free length to l_0

$\alpha_3 \dot{l}$ term damps oscillation of tether free length

New dimensionless variables $\varepsilon_l \ll 1$ and $\varepsilon_\delta \ll 1$ denote the deviation of the solution from the stationary point

$$l = l_0 (1 + \varepsilon_l), \qquad \delta = l_0 \left(\frac{\delta_s}{l_0} + \varepsilon_\delta \right)$$

Linearized equations

Linearized system:

$$\ddot{\varepsilon}_l = -\alpha_2 \varepsilon_l - \alpha_3 \dot{\varepsilon}_l + \alpha_1 \dot{\varepsilon}_\delta$$

$$\ddot{\varepsilon}_\delta = \left(\alpha_2 + \frac{T_0}{l_0 m_{12}} - 3k^4\omega_0^2\right)\varepsilon_l + \alpha_3 \dot{\varepsilon}_l + \left(\frac{T_0}{m_{12}\,\delta_s} - 3k^4\omega_0^2\right)\varepsilon_\delta + \alpha_3 \dot{\varepsilon}_l - \alpha_1 \dot{\varepsilon}_\delta$$

where

$$k = \frac{l_0}{l_0 + \delta_s} < 1, \qquad T_0 = \frac{EF}{l_0}\delta_s$$

Stability of the system = $f\,(\alpha_1, \alpha_2, \alpha_3)$

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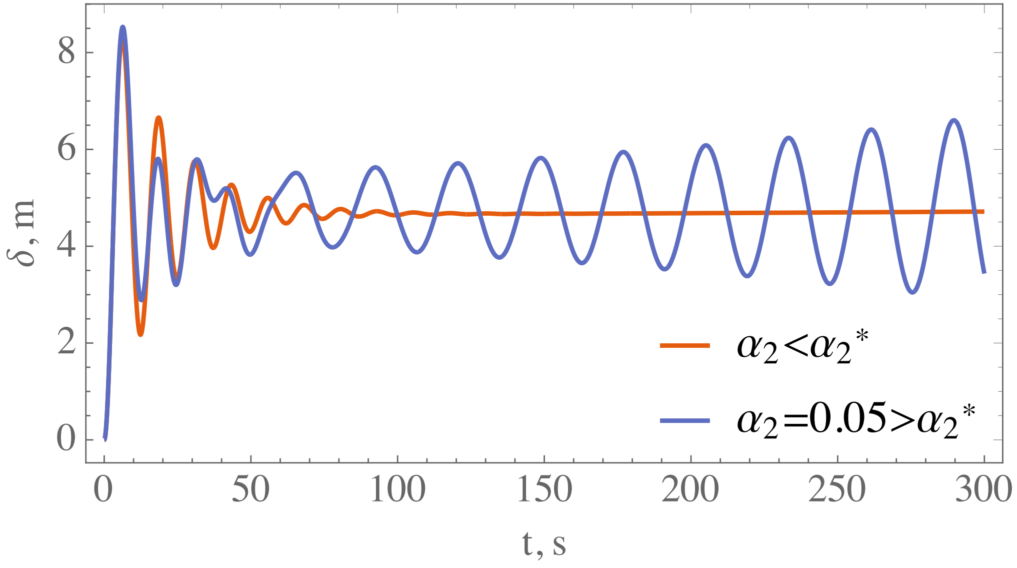
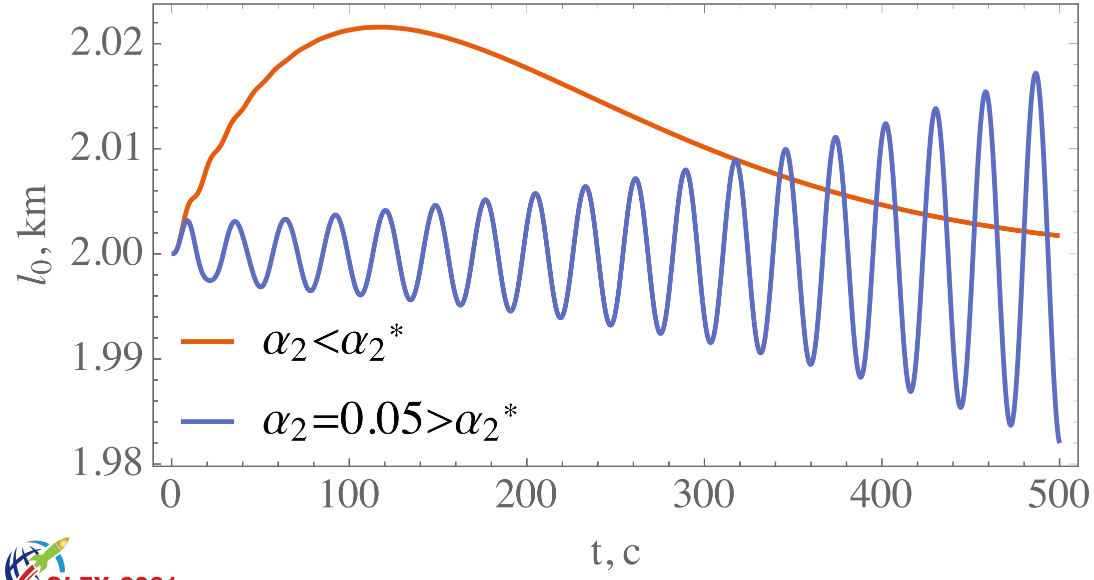
Stable motion conditions

$\alpha_1 = 0.1, \quad \alpha_2^* = 0.0353, \quad \alpha_3 = 0.015$





From Hurwitz stability criterion:

- Region I

$$\alpha_1 > 0, \qquad \alpha_3 > \alpha_3^*, \qquad 0 < \alpha_2 < \alpha_2^*$$

- Region II

$$\alpha_1 < 0, \qquad \alpha_3 > -\alpha_1, \qquad \alpha_2 > \alpha_2^*$$

where

$$\alpha_2^* = 3\,k^4\omega_0^2 + T_0\,\frac{l_0\alpha_3 - \alpha_1\delta_s}{l_0 m_{12}(\alpha_1 + \alpha_3)\delta_s}$$

$$\alpha_3^* = \frac{T_0 - 3k^4\,l_0\mathrm{m}_{12}\omega_0^2}{T_0 + 3k^4\,l_0\mathrm{m}_{12}\omega_0^2}\,\frac{\alpha_1\delta_s}{l_0}$$

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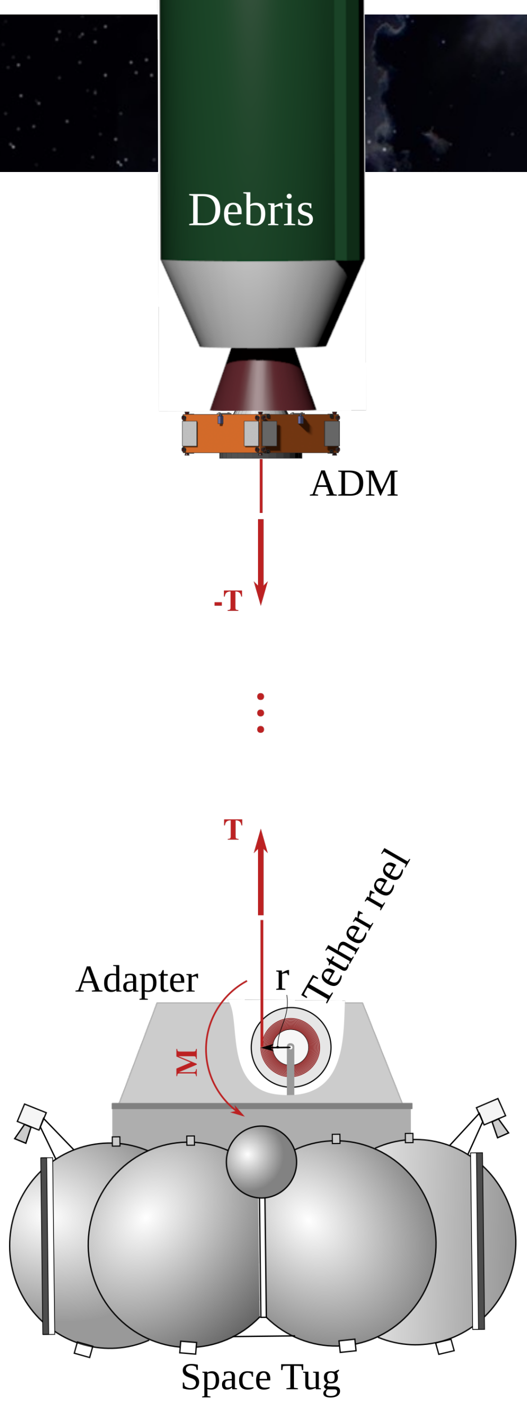
Motion of the tether reel



- Tether reel equation

$$J_r \ddot{\varphi} = T \cdot r - M \quad \Rightarrow \quad J_r \ddot{l} = T \cdot r^2 - M \cdot r$$

l_0 - tether free length;

J_r - moment of inertia of the reel;

r - reel radius

- Reel motor torque

$$M = \frac{EF}{l_0} \delta \cdot r - \frac{J_r}{r} [\alpha_1 \dot{\delta} - \alpha_2 (l - l_0) - \alpha_3 \dot{l}]$$

*It is assumed the space tug maintains the angular position

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Example

- **Phase 1 (Post capture phase)**

The distance between the tug and debris is of 2 km, the relative velocity is of 50 m/s.

Damping the tether oscillations

- **Phase 2 (pulling the tether)**

Decreasing the tether length from 2.0 to 1.5 km

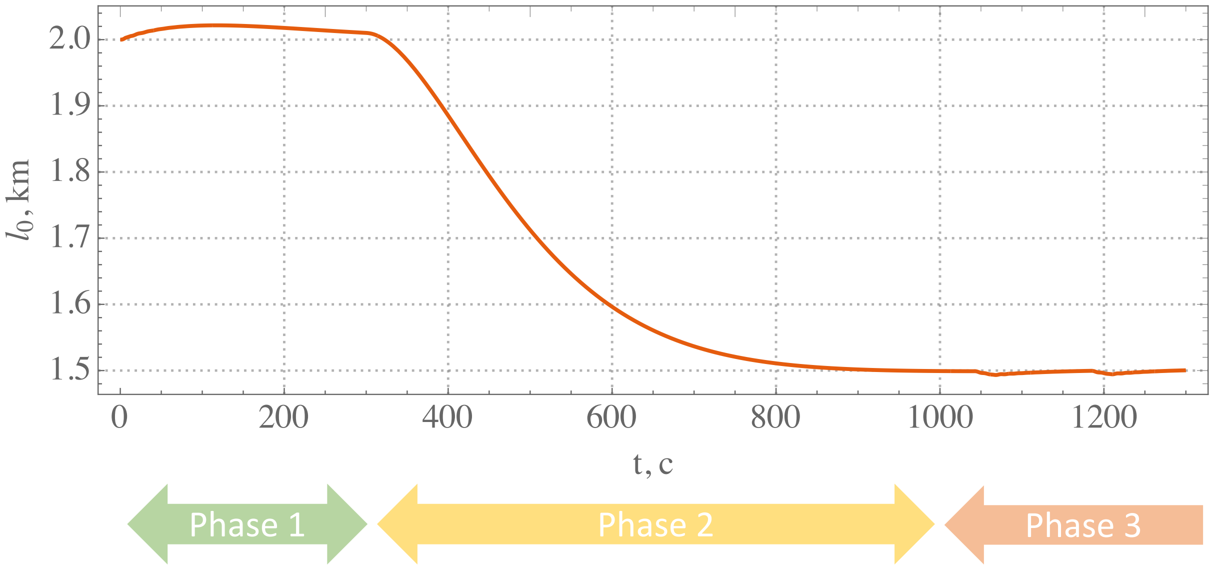
- **Phase 3 (active phase)**

Damping the tether oscillations upon thruster's switching on and off

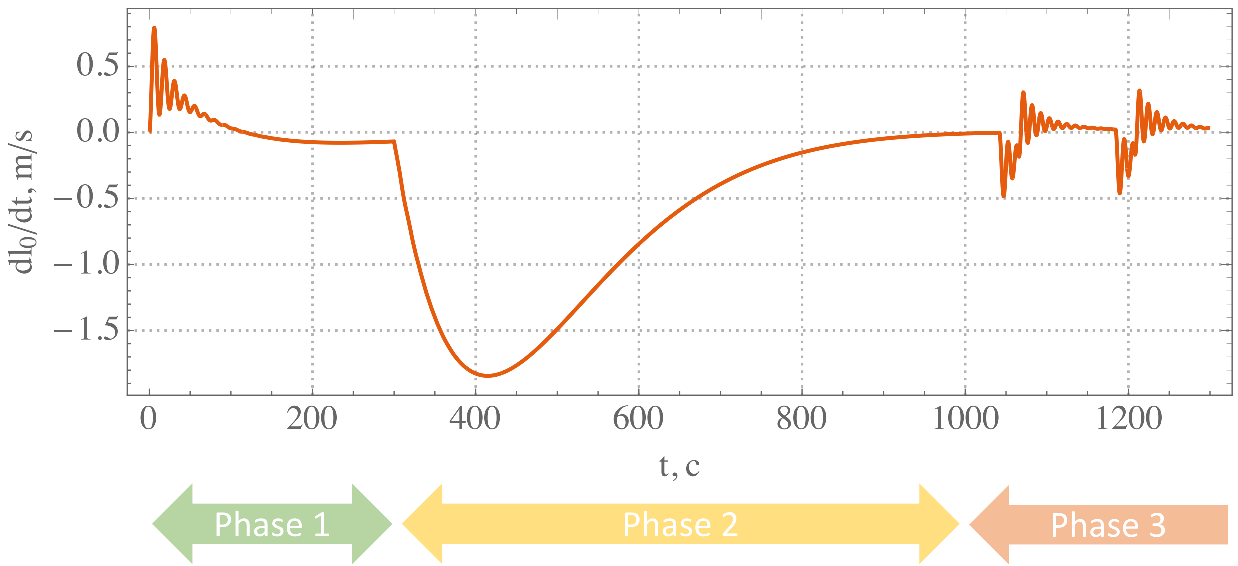
Parameter	Value
Debris mass	1700 kg
Tug mass	3000 kg
Initial tether length (capture length)	2000 m
Final tether length	1500 m
Tether Young's modulus (Kevlar)	81 GPa
Tether cross-section diameter	3 mm
Initial angular rate ($l = 2$ km), ω_0	1.4 °/s
Final angular rate ($l = 1.5$ km), ω	2.5 °/s
Tug's thrust	3000 N
α_1	0.1
α_2	$8 \cdot 10^{-5}$
α_3	0.015

Results

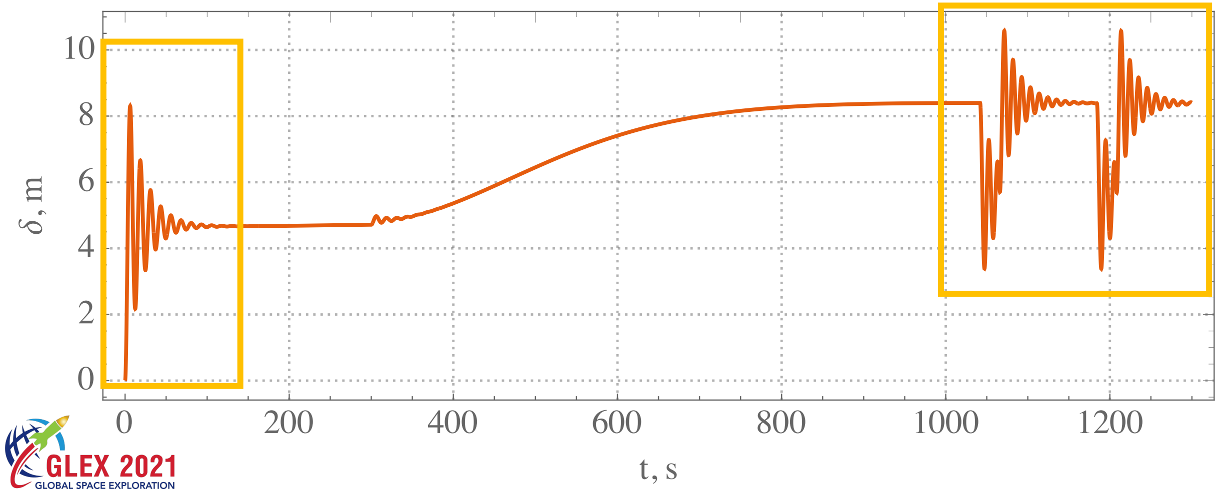
Tether free length



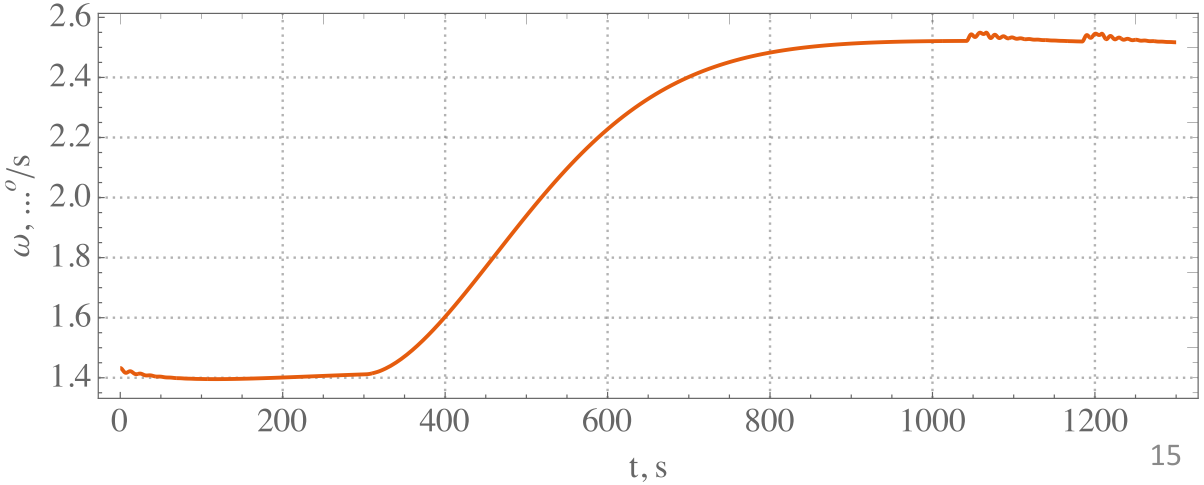
Tether free length rate



Tether deformation



TSS angular rate



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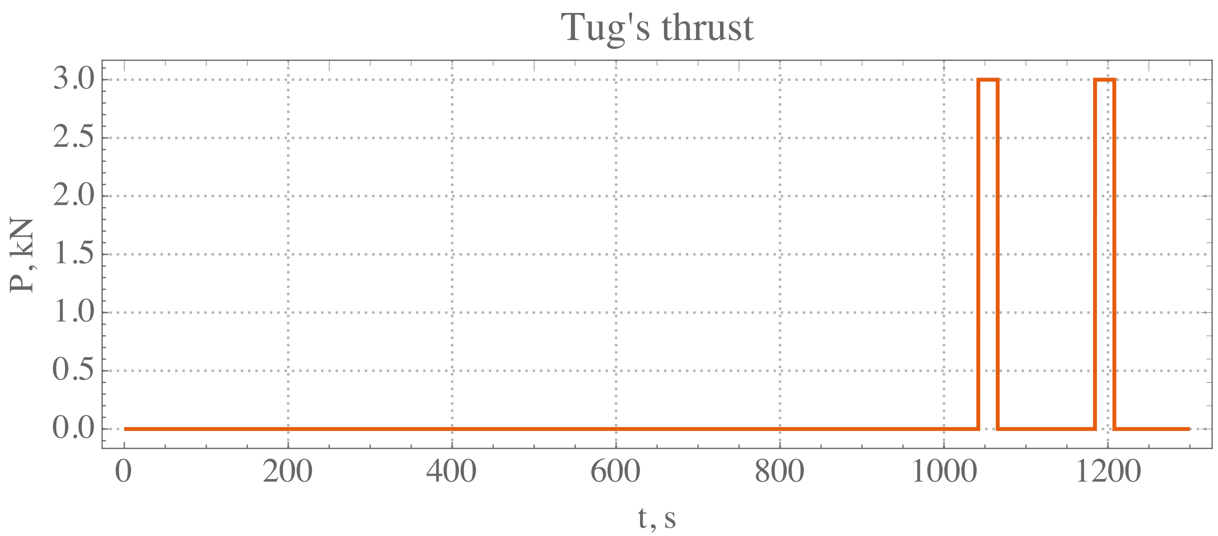
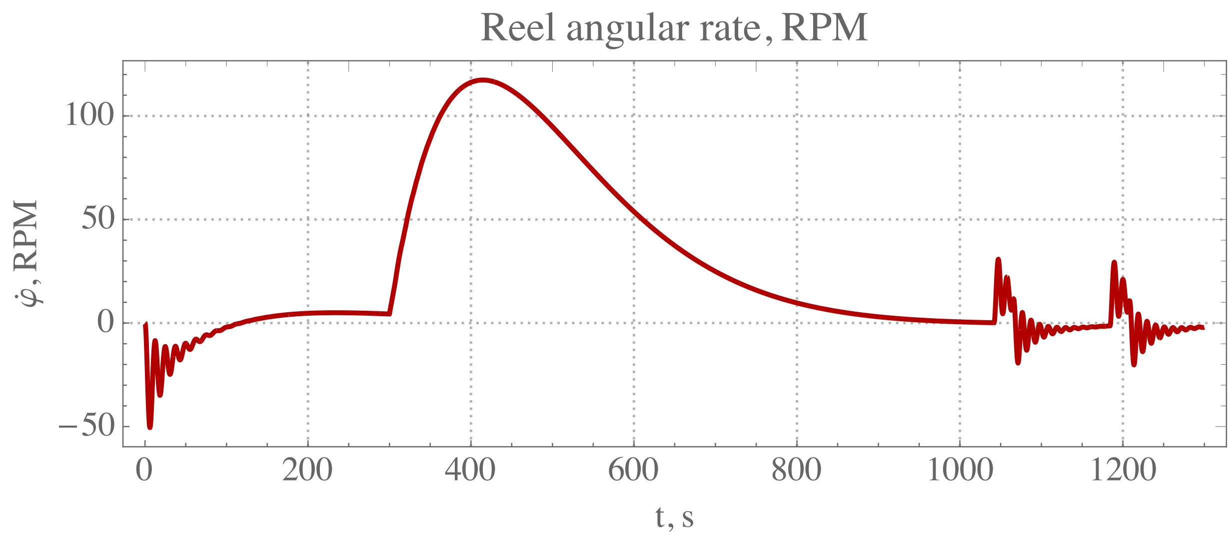
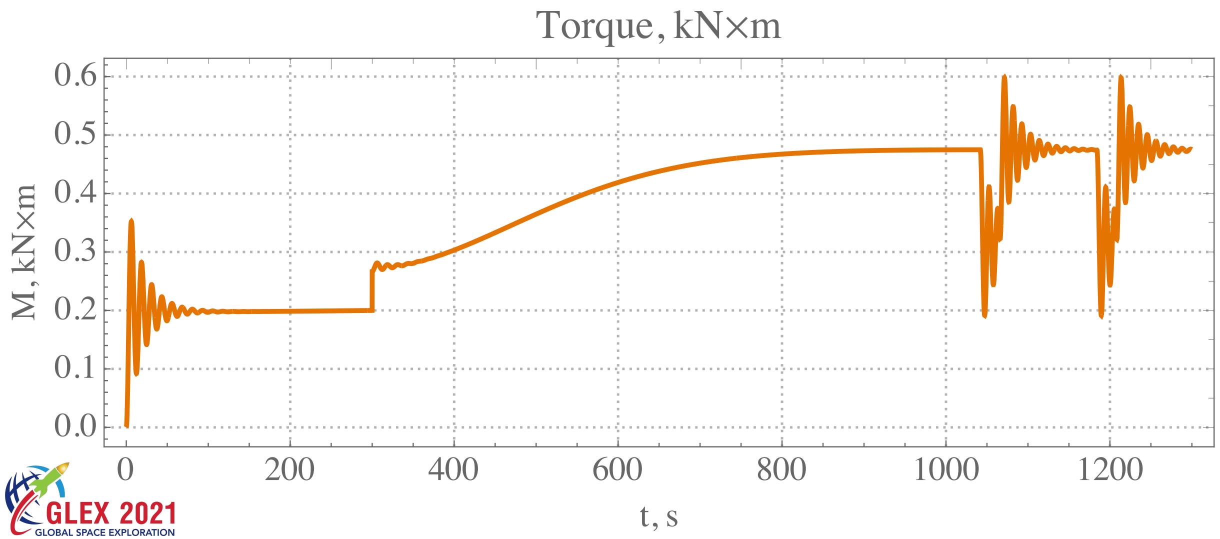
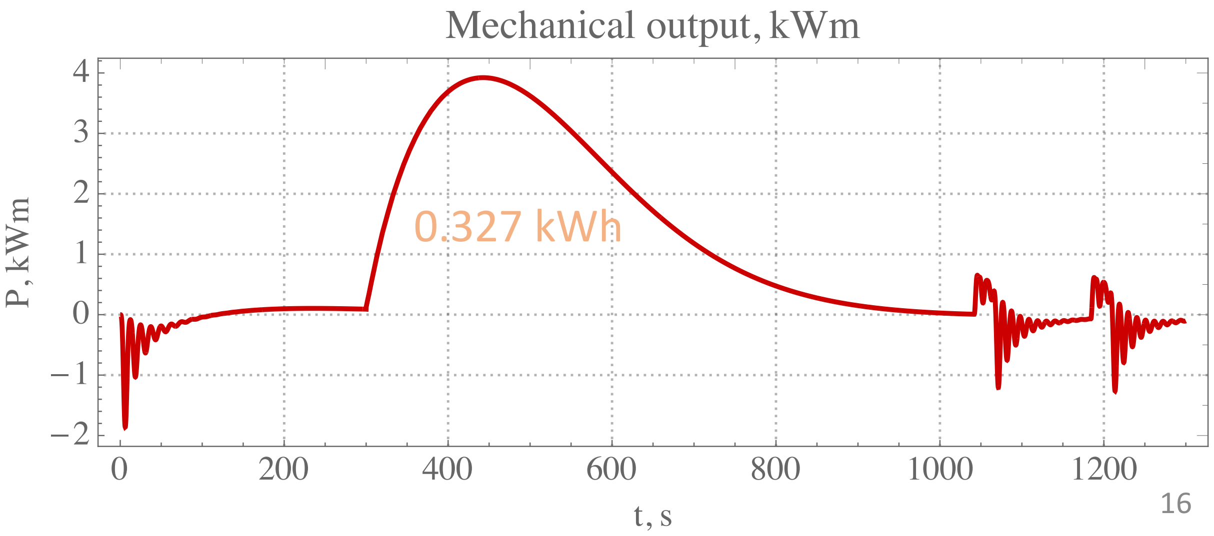
Results









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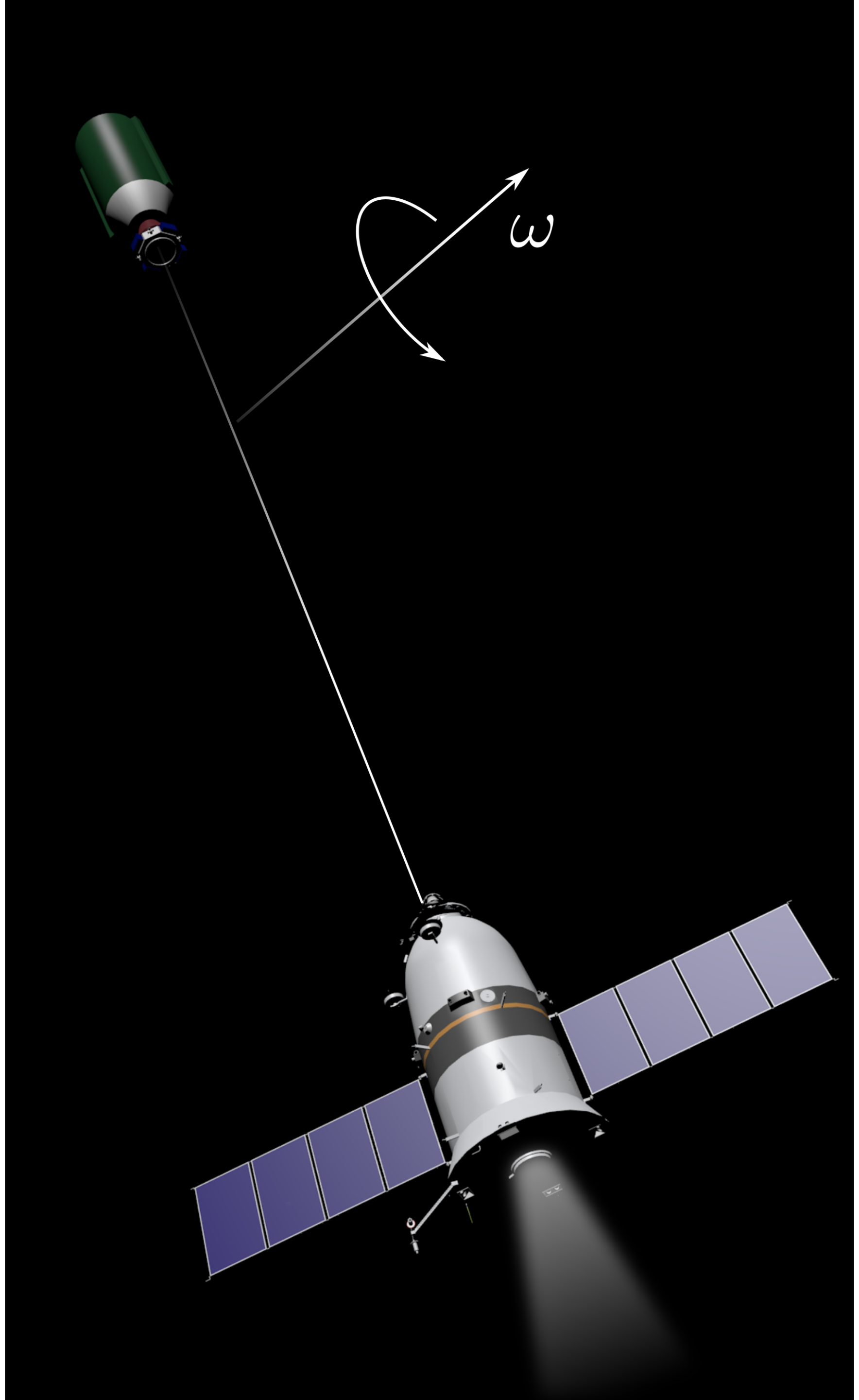
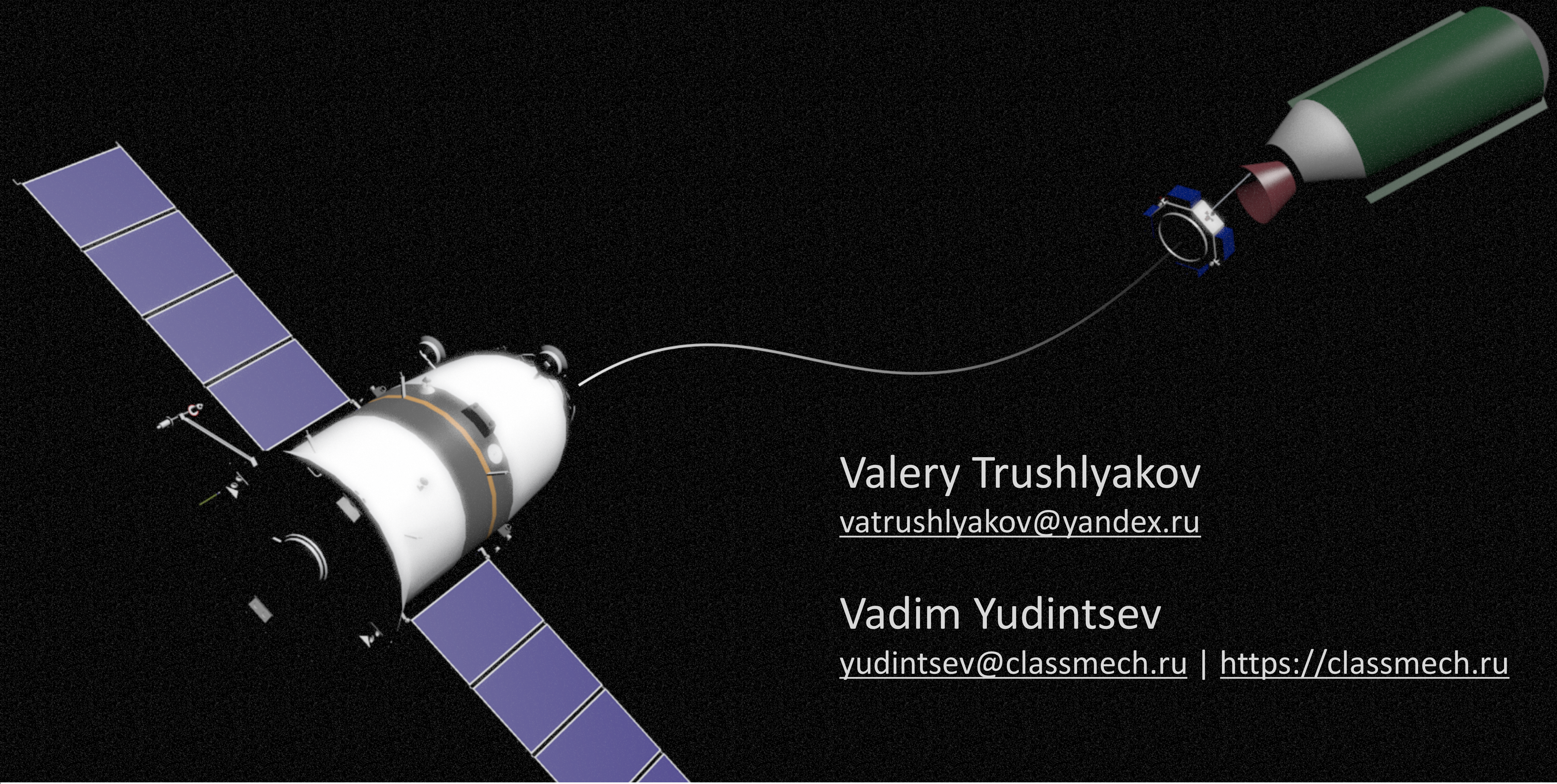


Conclusion

- A model of longitudinal oscillations of the rotating space tether system is proposed.
- A simple control law for the free length of the tether is presented, which damps the longitudinal oscillation of the tether.
- The required power for the electric drive of the tether reel is estimated.



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