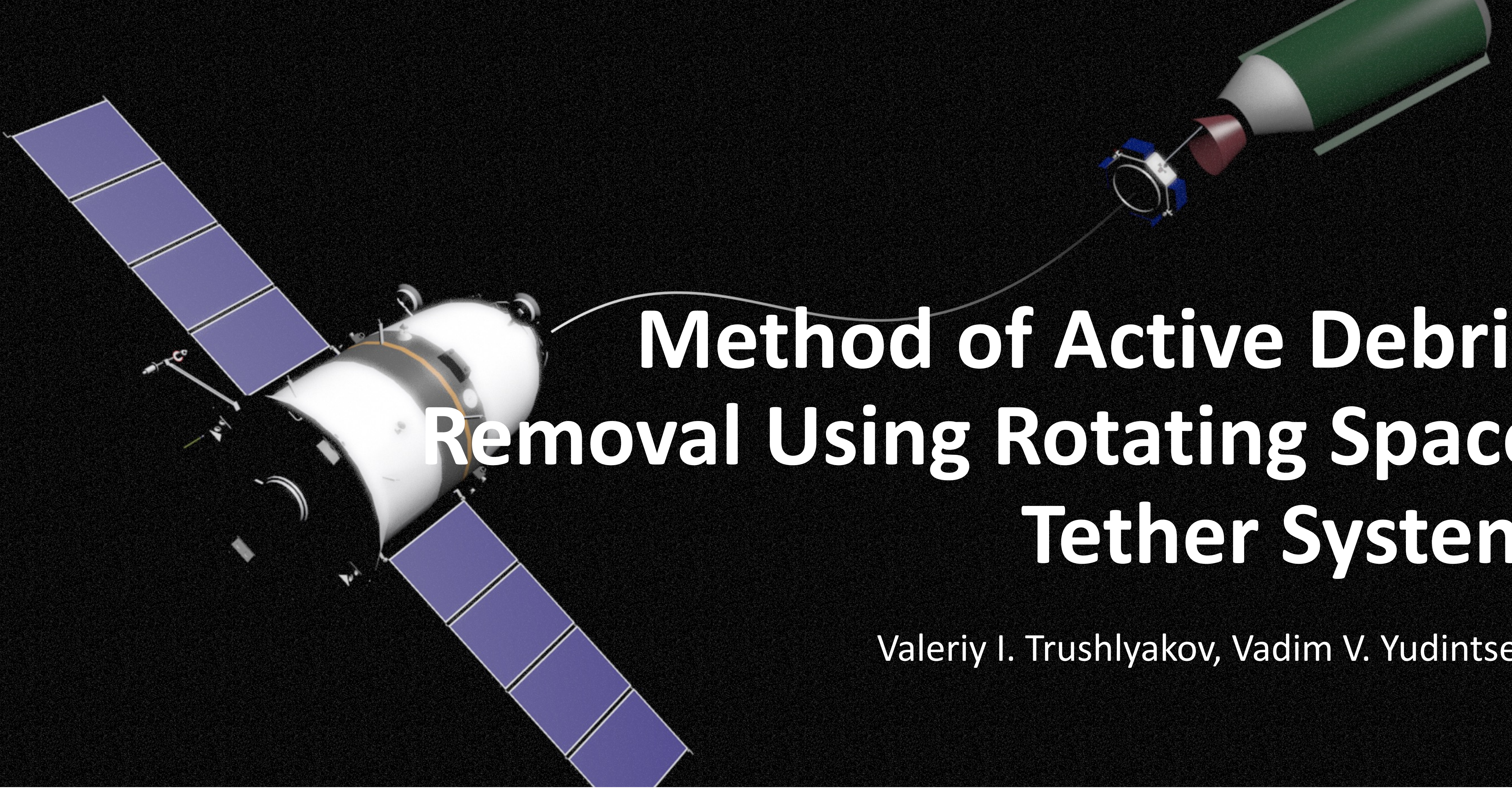

# Method of Active Debris Removal Using Rotating Space Tether System

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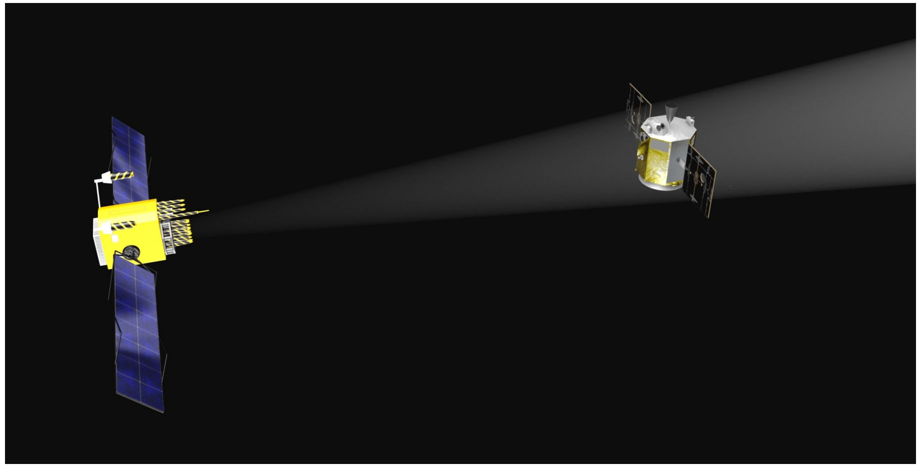
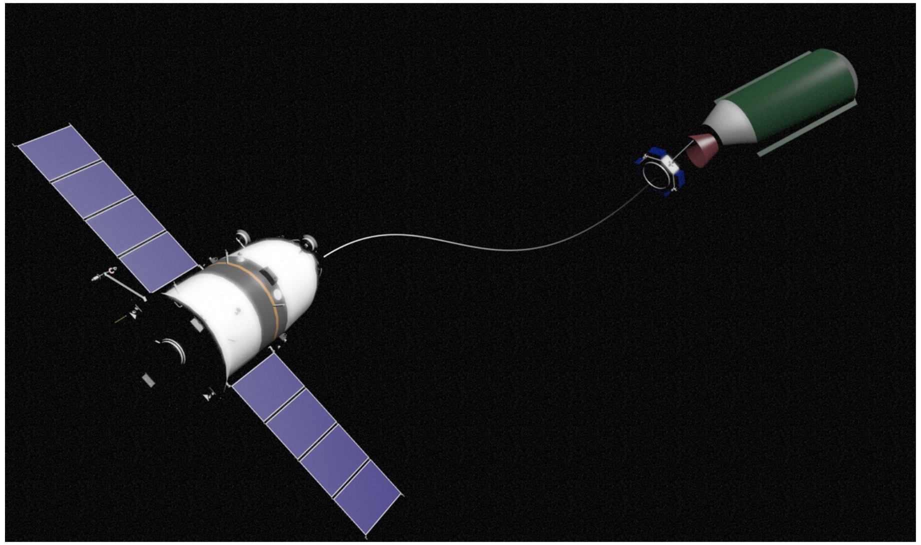
# ADR methods with mechanical contact



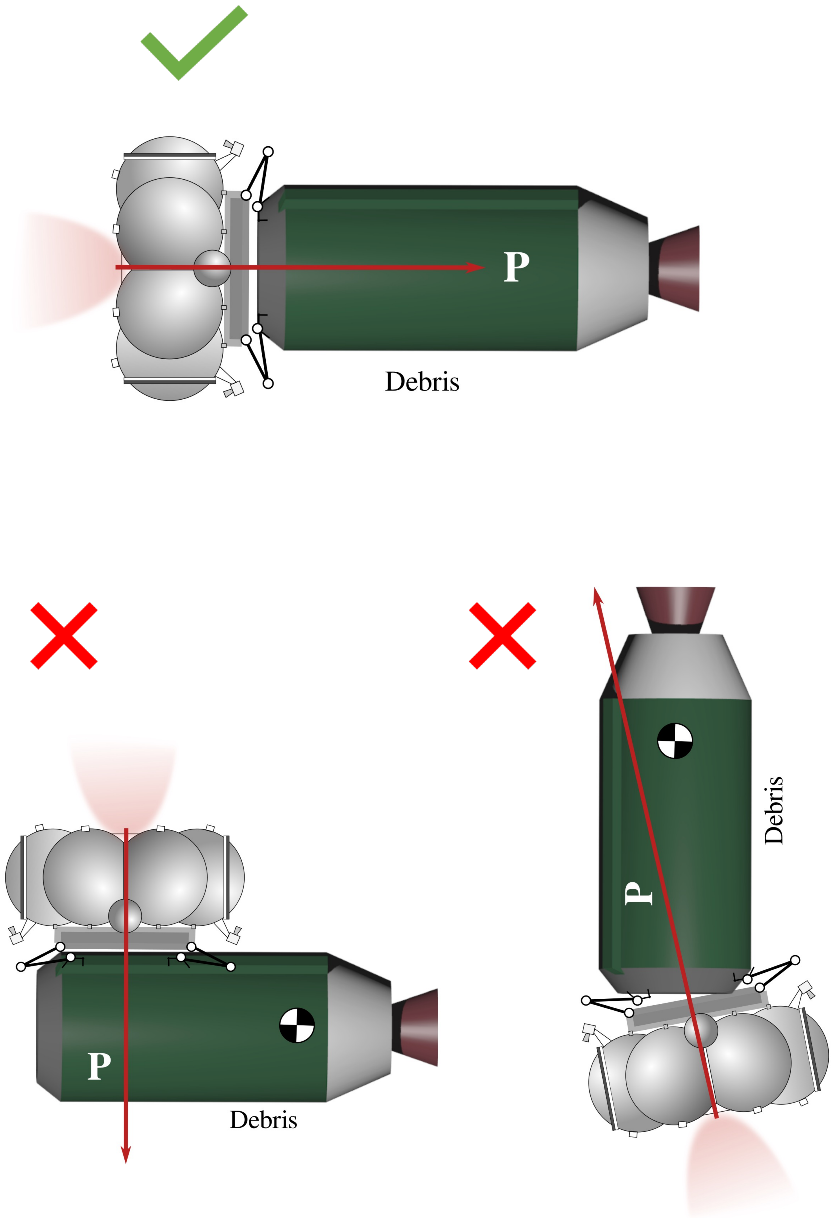


**A**ctive **D**ebris **R**emoval methods with mechanical interaction between the space debris and space tug

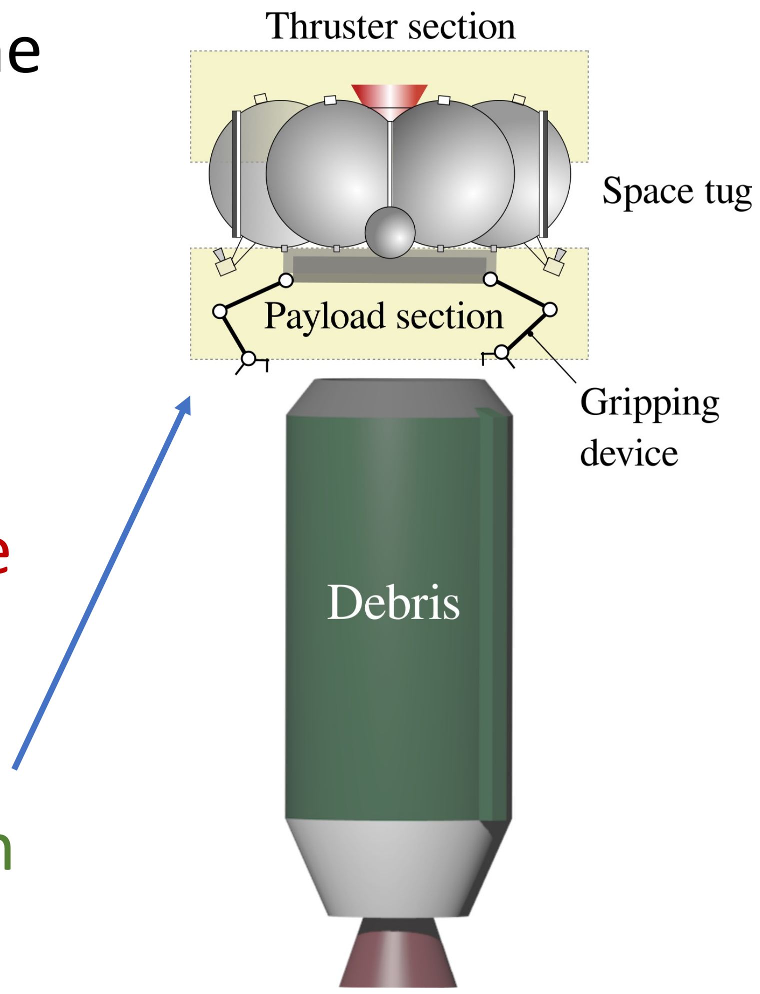
- Hard mechanical interface
  - Robotic manipulators, tentacles
  - Docking devices (probe-cone)
- Soft mechanical interface
  - Net + tether
  - Harpoon + tether

Bonnal, C., Ruault, J.-M., & Desjean, M.-C. (2013). Active debris removal: Recent progress and current trends. Acta Astronautica, 85, 51–60.

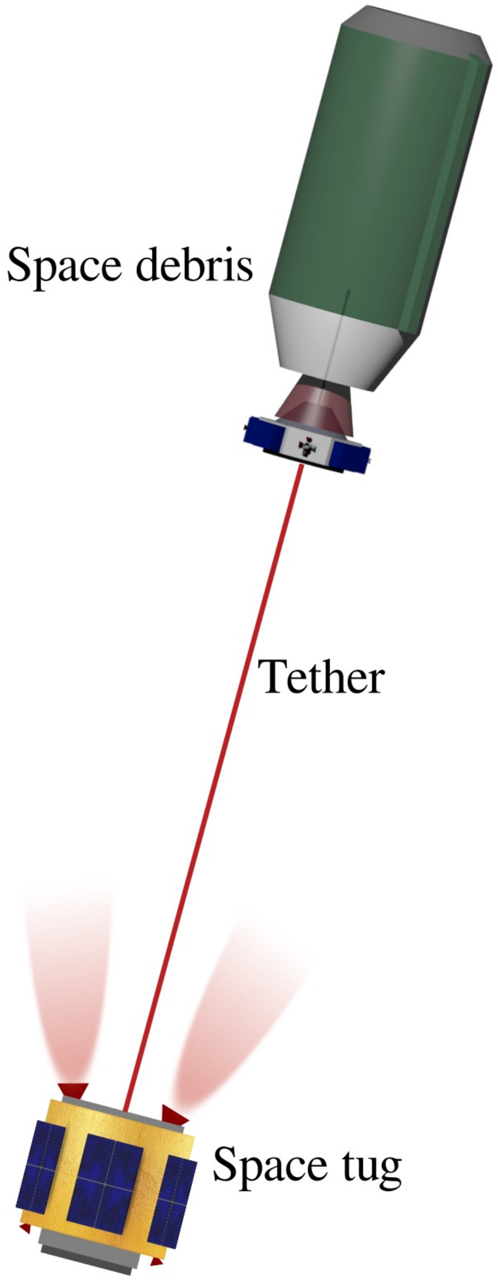
# Hard mechanical interface




- Robotic arm, probe-cone docking device
- Space tug **pushes** the debris object
- Stability of the system depends on the capture point and gripper type
- The space tug with conventional design can be used

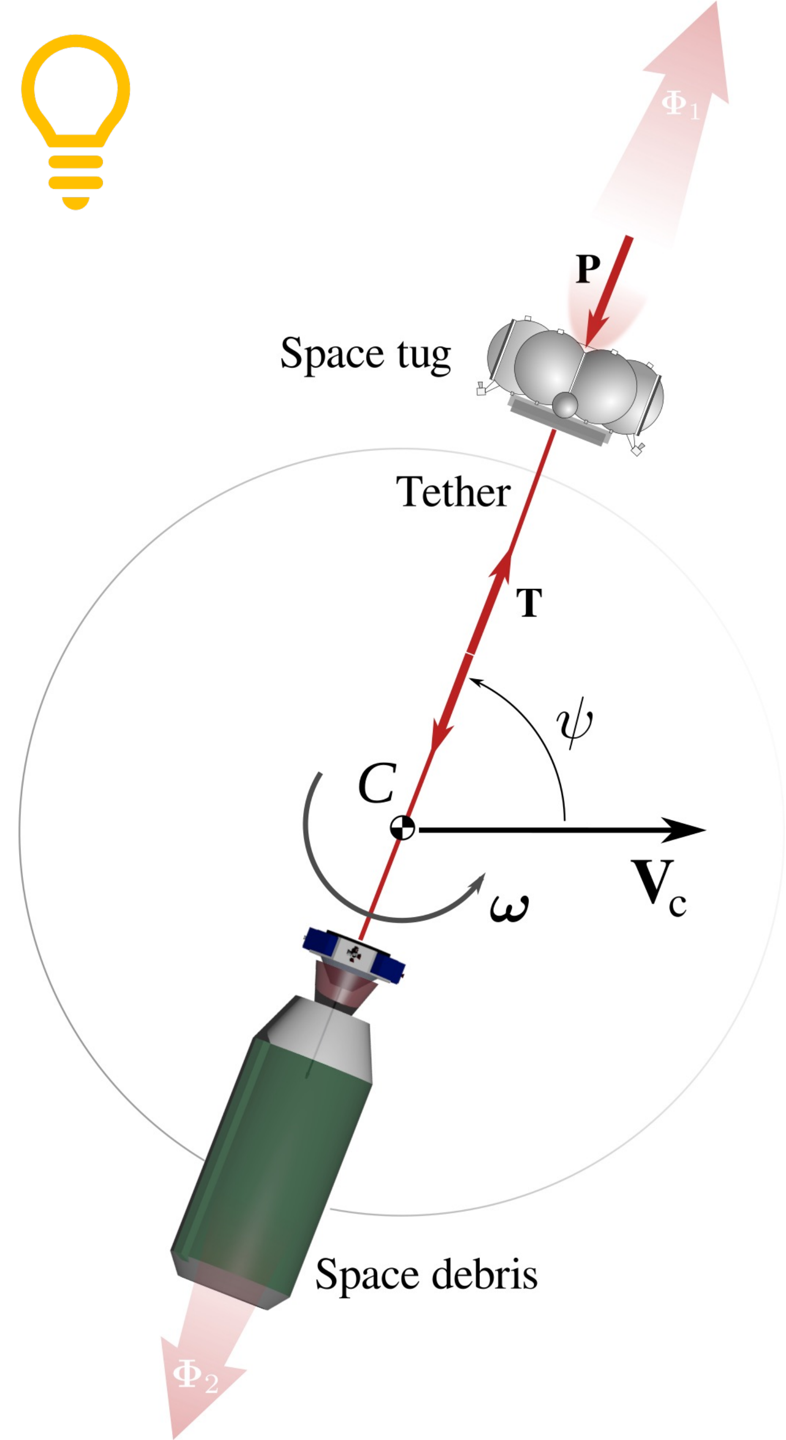


# Soft mechanical interface




- (Harpoon, net) + tether
- Space tug **pulls** the debris object
- Gripping process is safe for the space tug
- Tumbling debris objects  can be captured
- Tether could be damaged by the tug’s thruster exhaust
- Payload section and the thrusters are at the same side of the space tug -- design of the space tug is not conventional

# Rotating TSS




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

$$m_{12}\omega^2 \boldsymbol{l} = \mathrm{c}(\boldsymbol{l} - l_0)$$

- Tether tension force

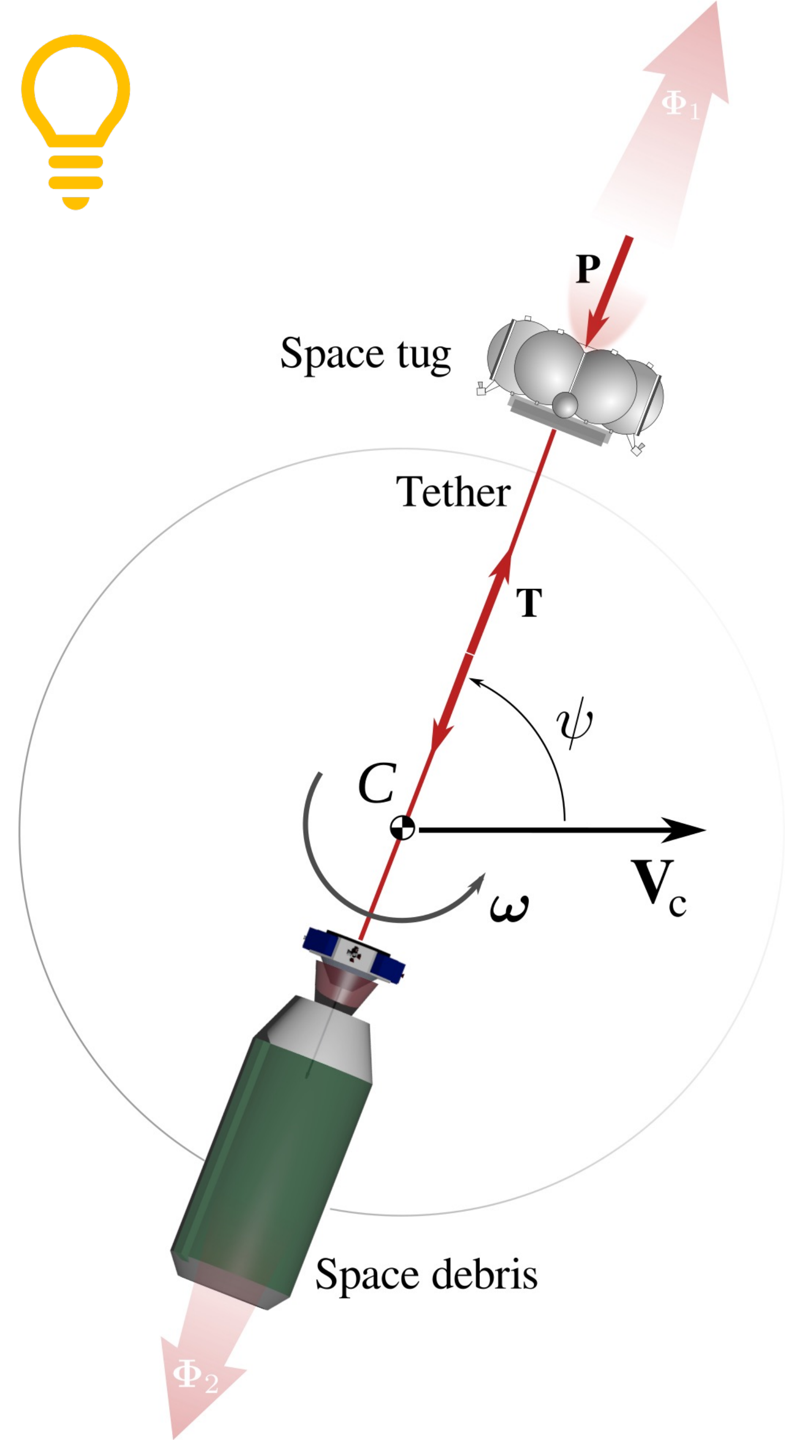
$$T = m_{12}\omega^2 \boldsymbol{l}$$

- **The tug's thrust P can be applied along the tether**

$$P < T$$

- The space tug can **push** the debris object through the tether

# De-orbiting TSS

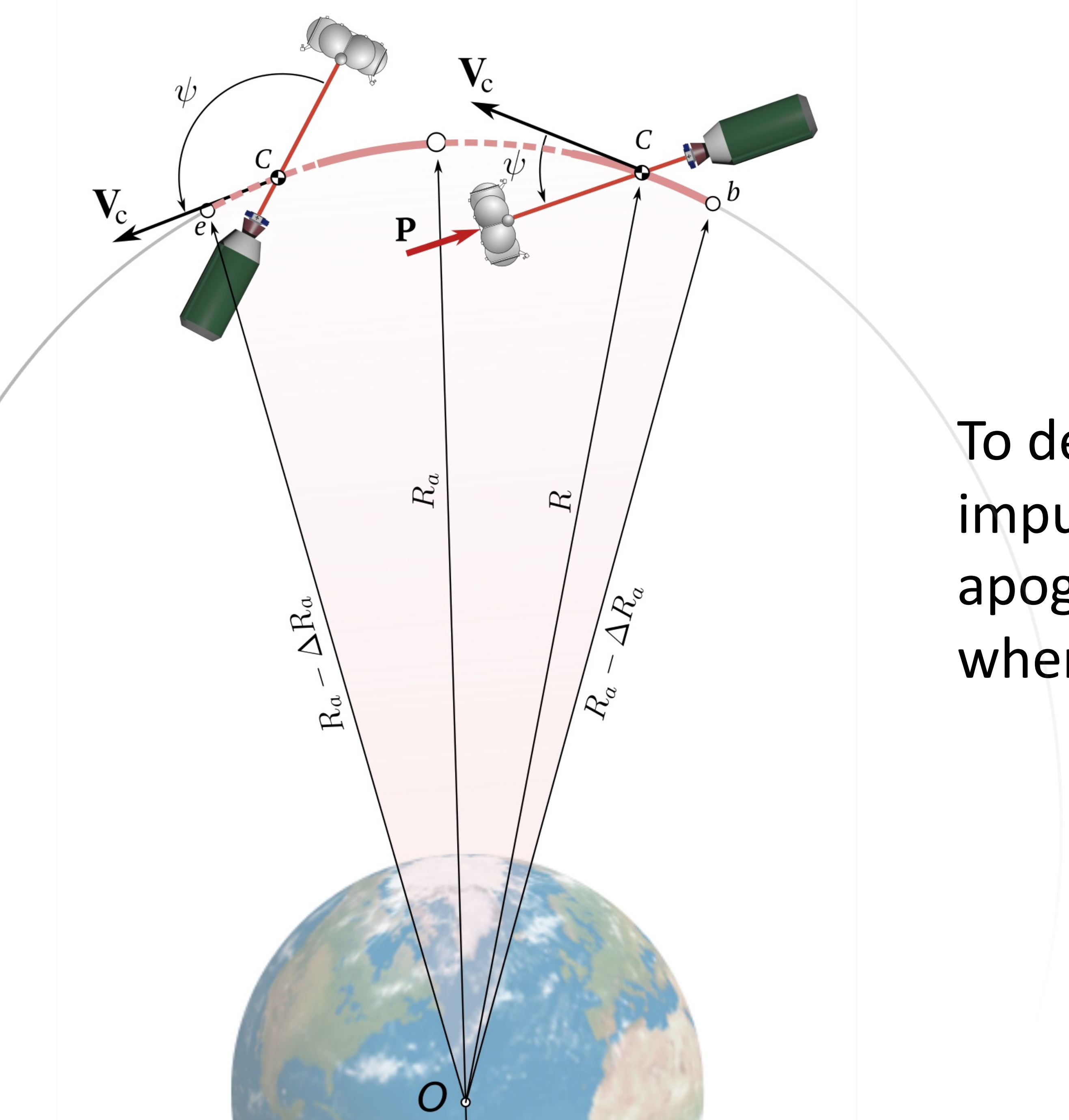



- The tug's thruster is fired when the orientation of the tether relative to the orbital velocity vector of the system ($\mathbf{V}_c$) ensures application of the tug's thrust impulse in the required direction
- To de-orbit the system the tug's thruster should be fired when

$$\cos\psi > \cos\psi_{min} > 0 \quad (1)$$

- (1) is the condition of the **active** phase of the rotating TSS de-orbit process

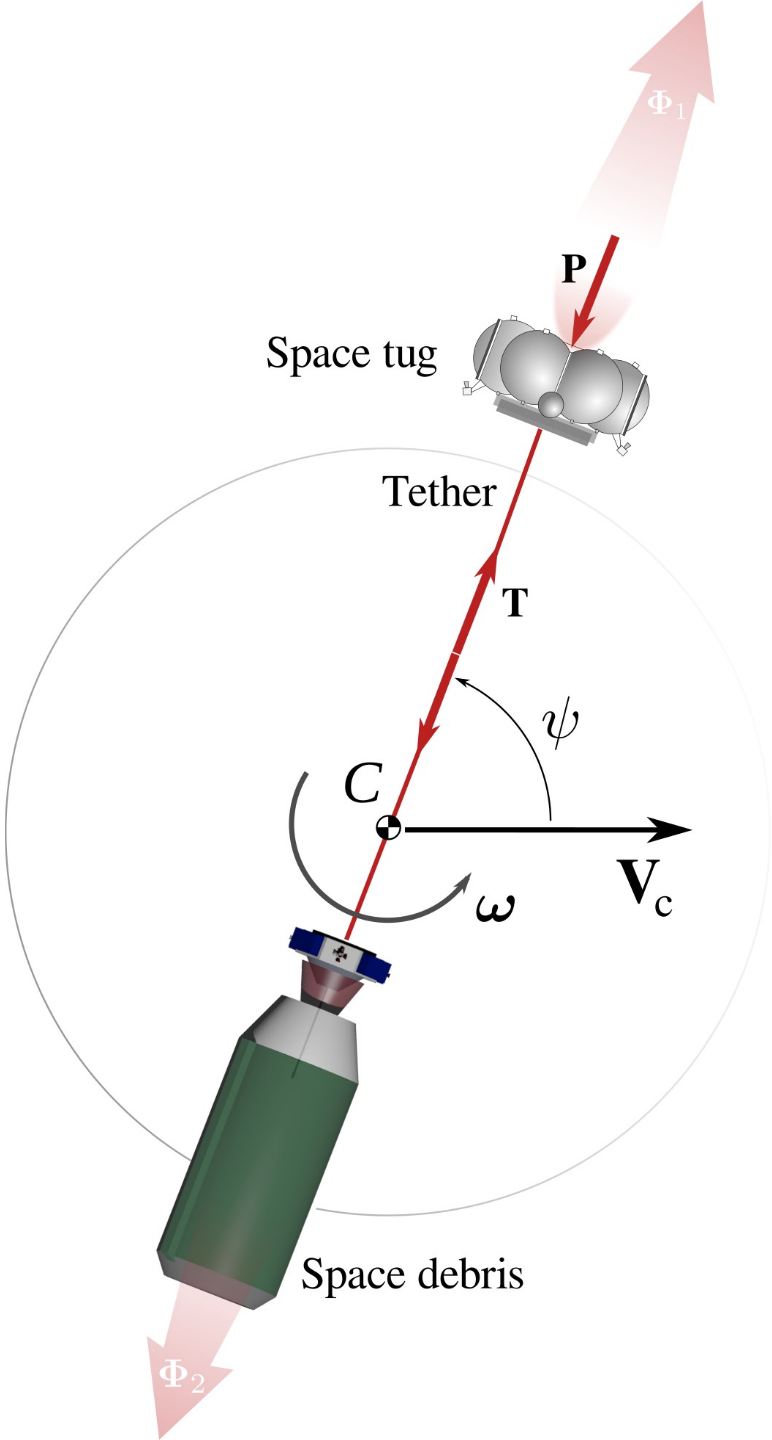
# De-orbit of the TSS




To decrease fuel consumption the de-orbit impulses can be applied only near the apogee of the system's osculating orbit, when

$$R > R_a - \Delta R$$

# Simple rotating TSS model




Tether length equation

$$\frac{d^2 l}{dt^2} = \omega_0^2 \frac{l_0^4}{l^3} - \frac{P}{m_\mathrm{T}} - k^2 (l - l_0)$$

$\omega_0$ - initial angular rate of the TSS when $l(0) = l_0$

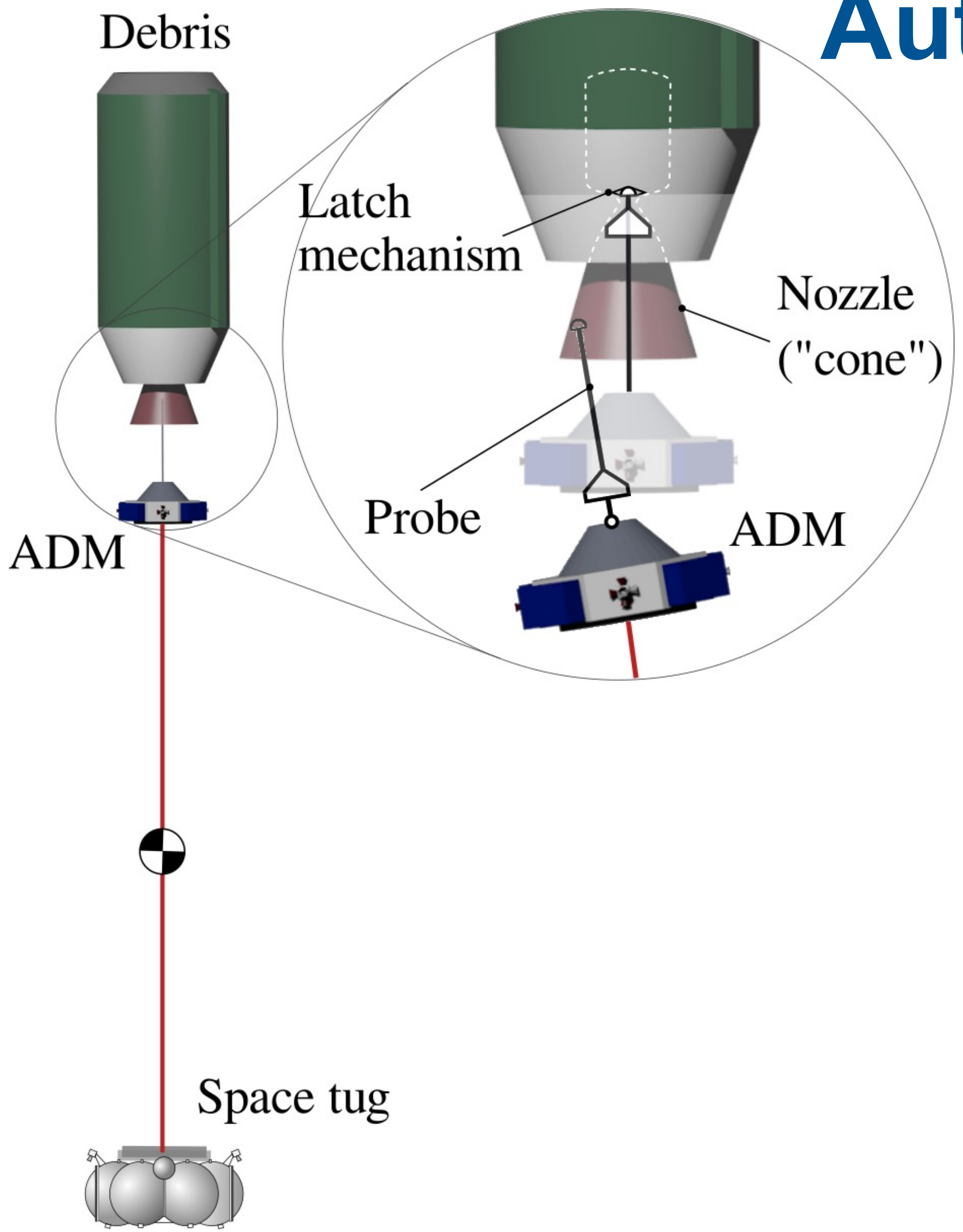
$m_\mathrm{T}$ - tug's mass*, $m_\mathrm{D}$ - debris mass

$l_0$ - free length of the tether, c – tether stiffness

$$k = \sqrt{\frac{c}{m_\mathrm{TD}}},\ m_\mathrm{TD} = \frac{m_\mathrm{T} m_\mathrm{D}}{m_\mathrm{T} + m_\mathrm{D}}$$

*It is supposed that $m_T$= const.

# Autonomous Docking Module

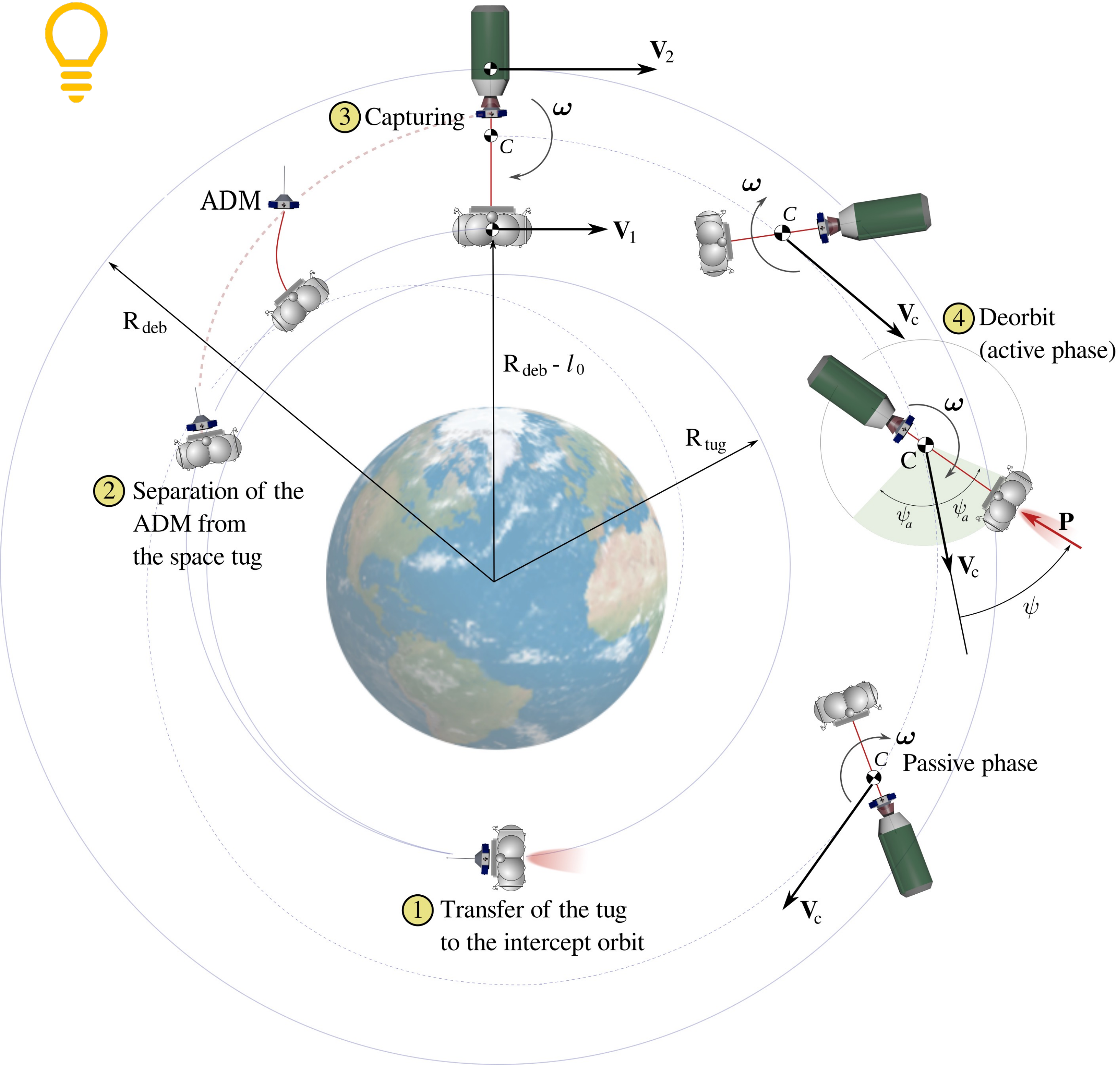



- Tethered connection between the tug and debris can be established by the **A**utonomous **D**ocking **M**odule
- ADM is a small spacecraft that carries all specific equipment for ADR mission
- ADM can use probe-cone* mechanism to dock with the upper-stage-type debris object using the nozzle of the debris as a docking port

*Trushlyakov, V. I., Shatrov, Y. T., Oleynikov, I. I., Makarov, Y. N., and Yutkin, E. A., "The method of docking spacecraft and device for its implementation. Patent RU 2521082." , 2010.

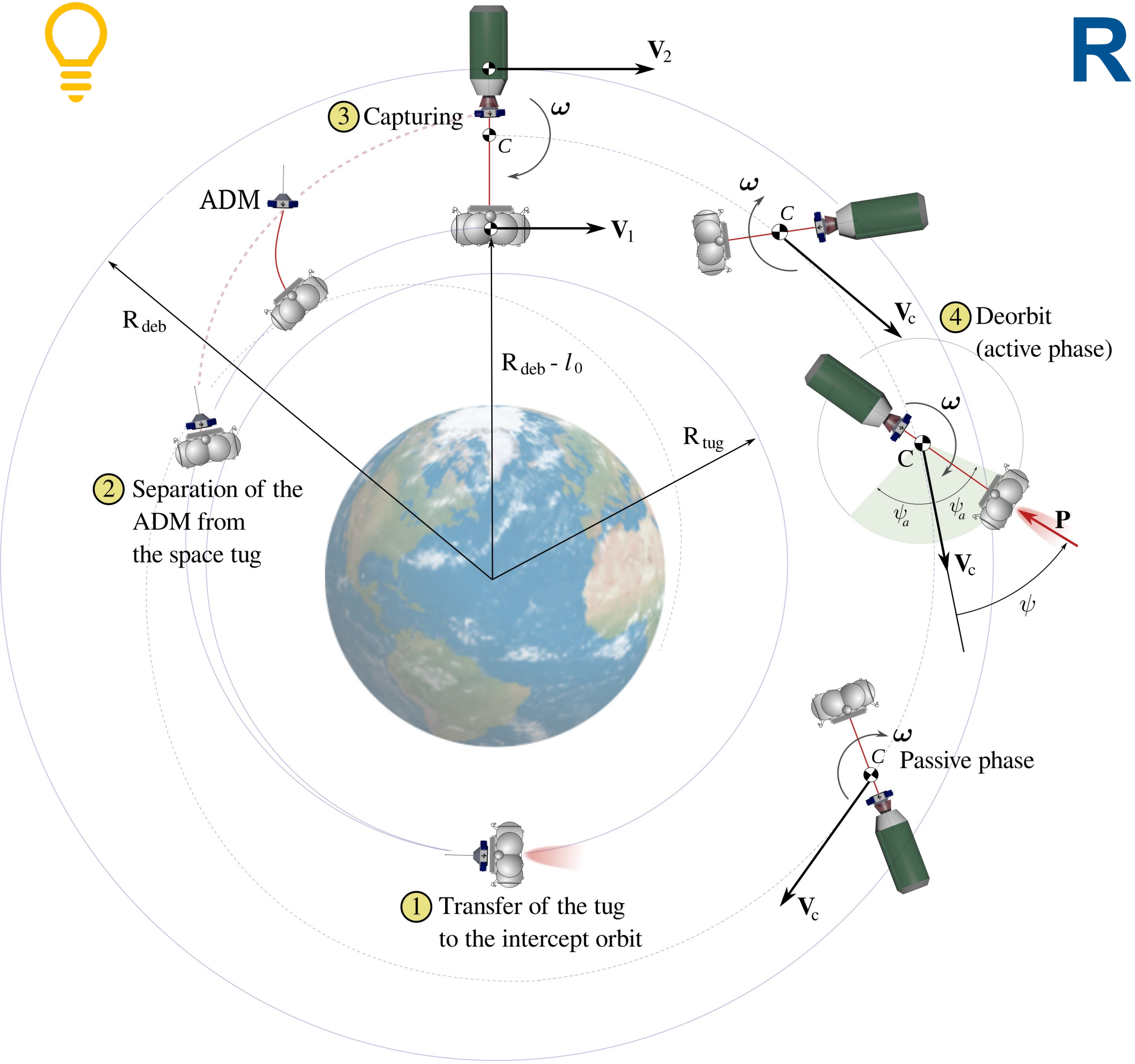
*Trushlyakov, V. I., and Yudintsev, V. V., "Systems engineering design and optimization of an active debris removal mission of a spent rocket body using piggyback autonomous module," 3rd IAA Conference on Dynamics and Control of Space Systems (DYCOSS 2017) 30 May - 1st June 2017, Moscow, 2017, pp. 667–681.

# Stages




- Transfer of the space tug to the intercept orbit
- Separation of the Autonomous Docking Module from the tug
- Gripping the debris object
- Transfer to a graveyard orbit

# Rotation of the TSS




- The required initial angular rate of the tethered system can be achieved by the relative orbital motion of the space tug and debris
- The space tug and debris have different orbital velocities, so the initial angular rate of the system is

$$\omega_0 = \frac{V_{deb} - V_{tug}}{l_0}$$

# Oscillation damping

*The rotation is not shown

- Applying tug's thrust along the tether can increase the oscillation amplitude of the tether that affects the oscillations of the debris and space tug relative to the tether
- The oscillations of the tether should be damped
- Stationary tether length

$$l_P^s = (k^2 l_0 - P/m_T)/(k^2 - \omega^2)$$

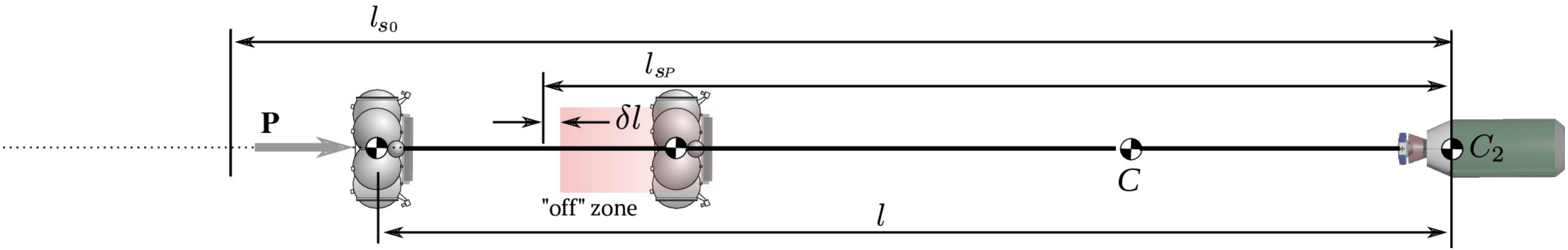
- Stationary tether length when P = 0

$$l_0^s = k^2 l_0/(k^2 - \omega^2)$$

# Tether damping

During the active phase the tug's thruster is off when the tether is less than $l_P^s$ and the length is decreasing

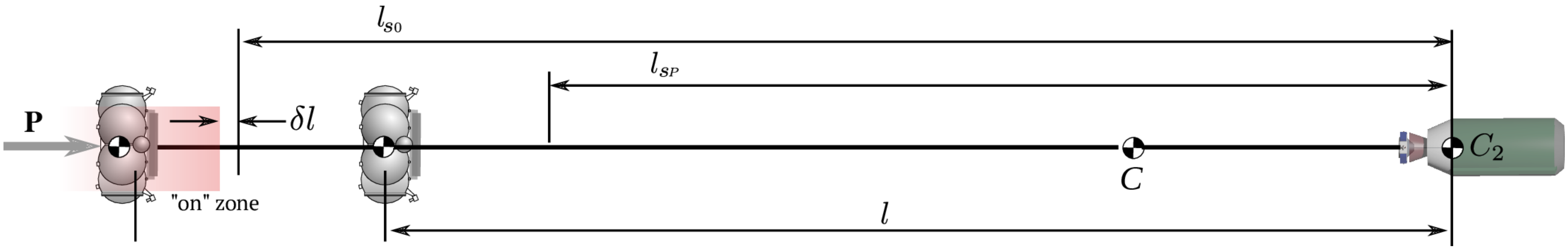
$$P = \begin{cases} 0 & l < l_P^s \wedge \dot{l} < 0 \\ P & \text{other cases} \end{cases}$$



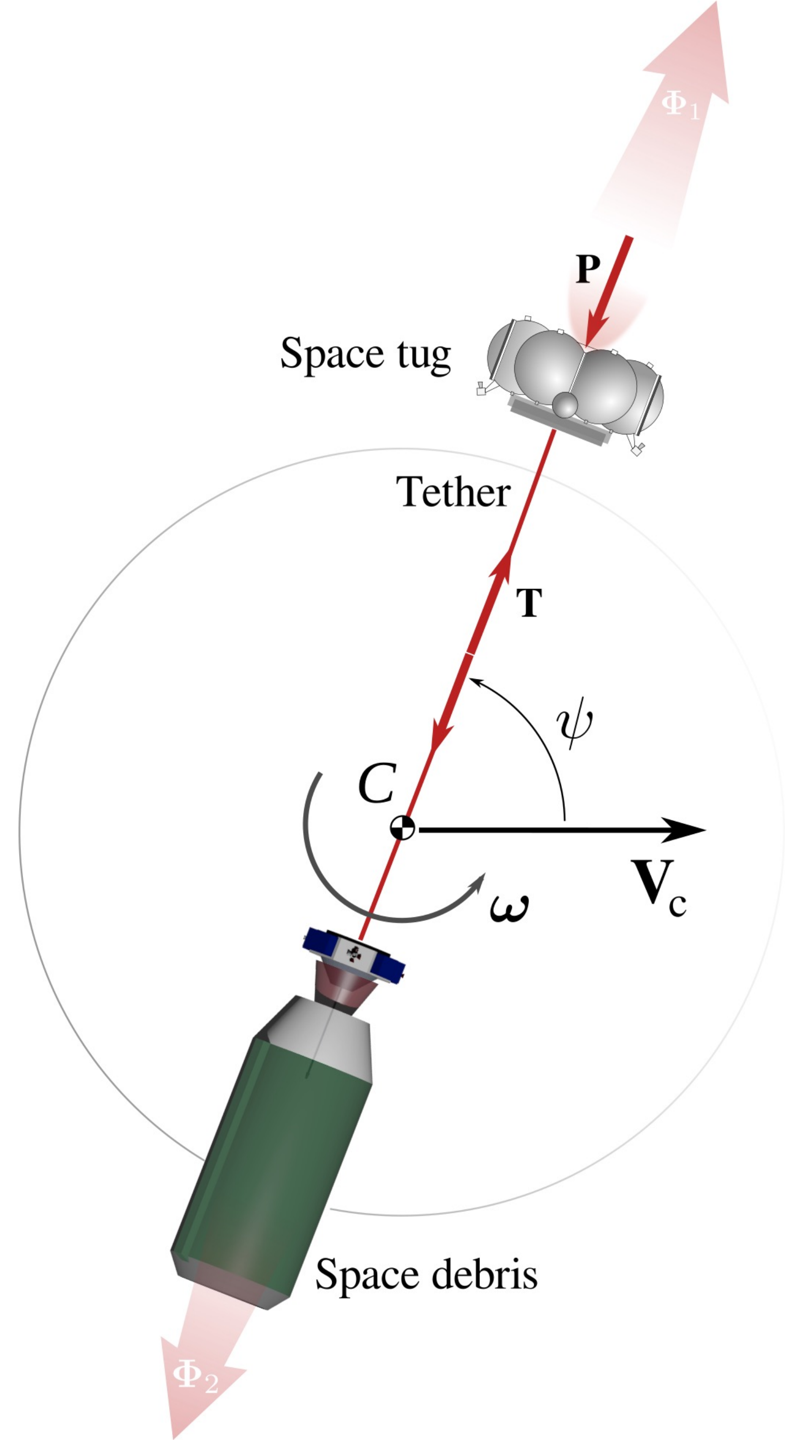
# Tether damping

- During the passive phase the thruster is fired when the tether length is greater than $l_0^s$ and the length is increasing

$$P = \begin{cases} P & l > l_0^s \ \wedge \ \dot{l} > 0 \\ 0 & \text{other cases} \end{cases}$$



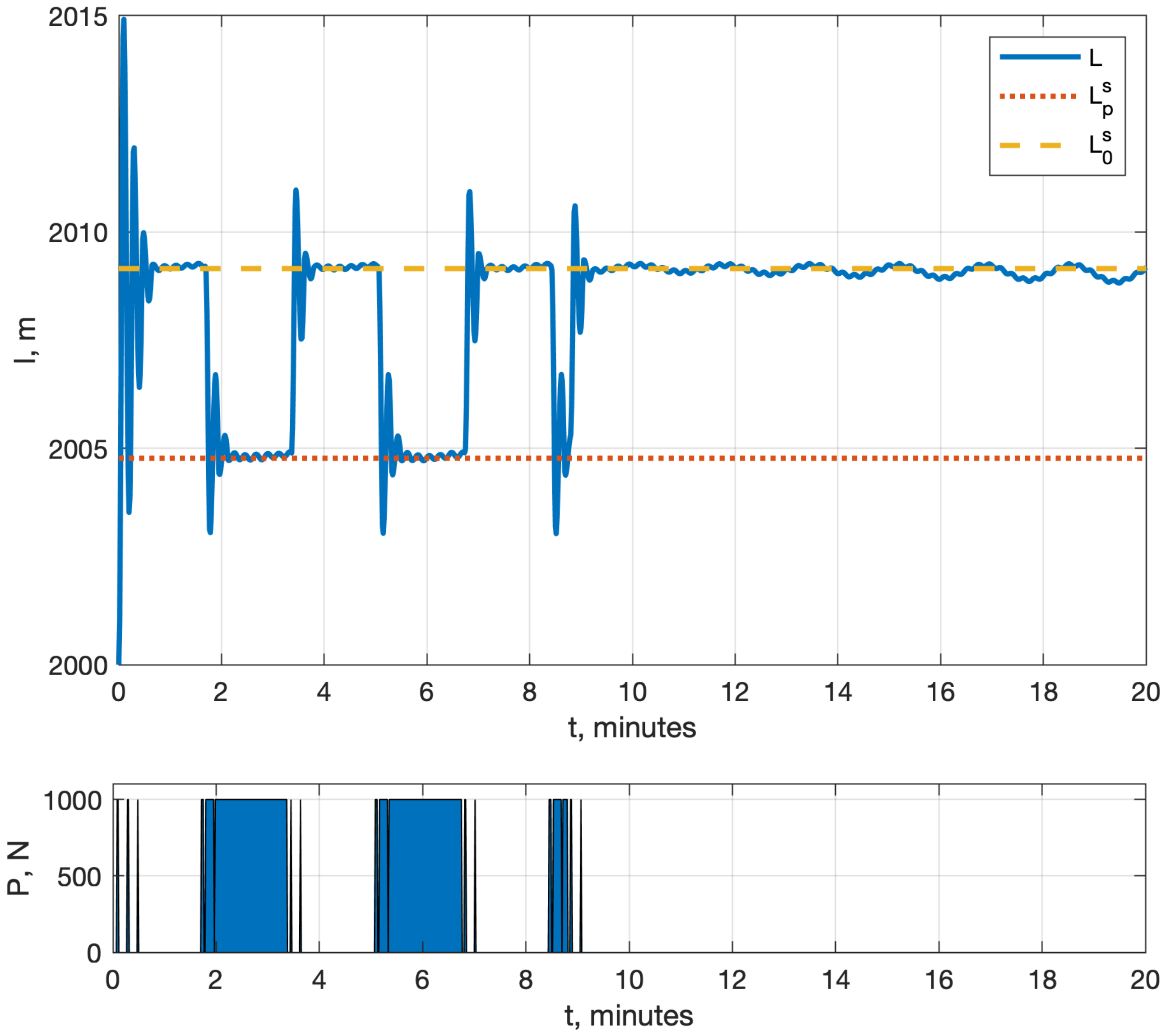
# Simulation




| Parameter | Value |
|---|---|
| Initial angular rate, deg/s | 1.85 |
| Initial tether length, м | 2000 |
| Space tug mass, kg | 1000 |
| Debris + ADM mass, kg | 1600 |
| Debris orbit, km | 800 x 800 |
| Tug’s thrust, N | 1000 |
| Young's modulus, GPa | 80 |
| Tether diameter, mm | 2 |

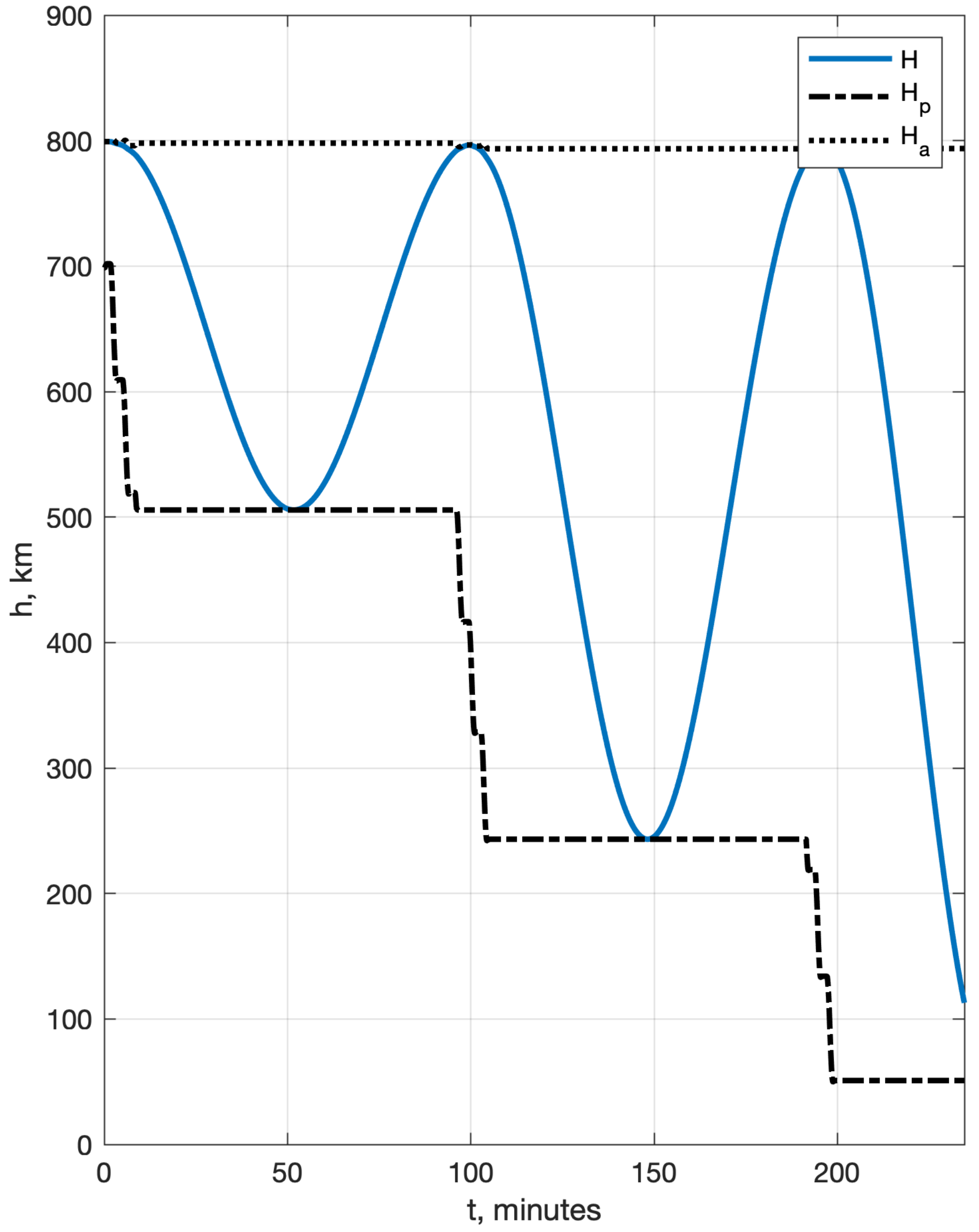
The mass of the debris object includes the ADM mass. The space tug and ADM use simple simple axis attitude control system. The control torque tries to align axis of each body (tug, debris+ADM) with the tether line.

# Tether deformation




- Tether deformation for the first 20 minutes
- Dashed and dotted lines designate stationary tether lengths
- Tug’s thruster diagram shows intervals when the tug’s thruster is in “ON” state

# Height of the TSS orbit




- Tug's thruster is fired near the apogee of the orbit when

  $R > R_A - 10 \text{ km and } \cos\psi > \cos(45\,^{\text{o}})$

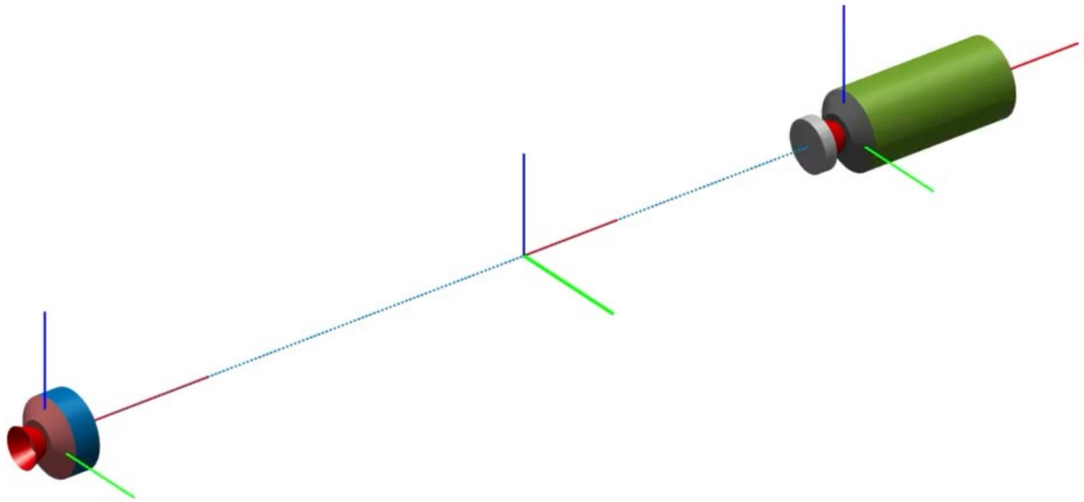
- De-orbit process lasts less than 250 minutes
- Fuel consumption for the de-orbit process: 265 kg

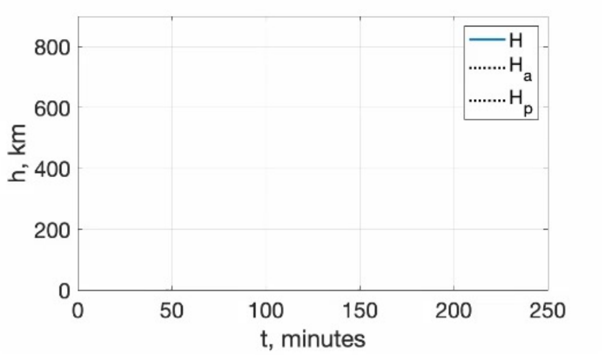
T = 0 s

ha = 806 km

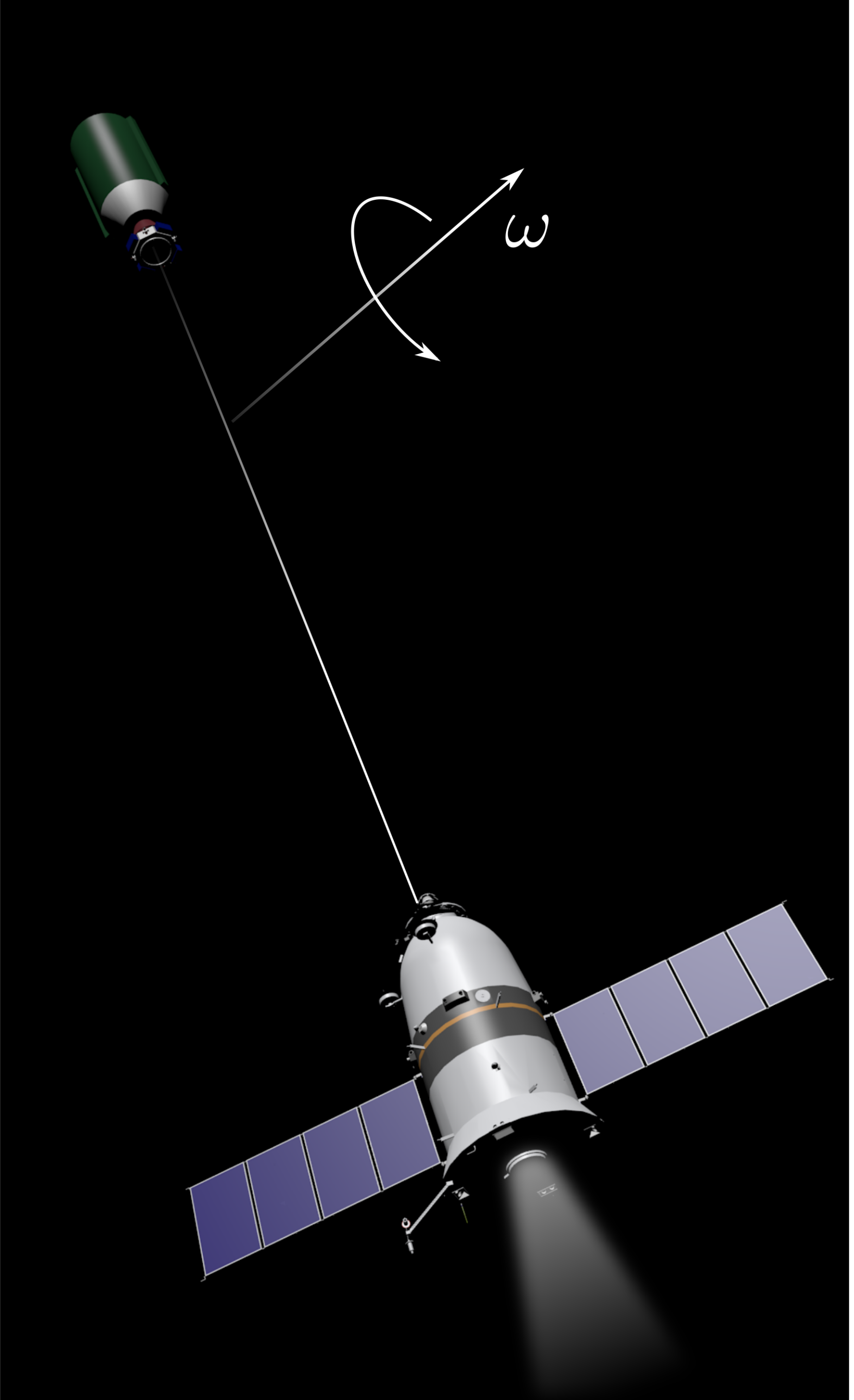
hp = 706 km

L = 2000.00 m



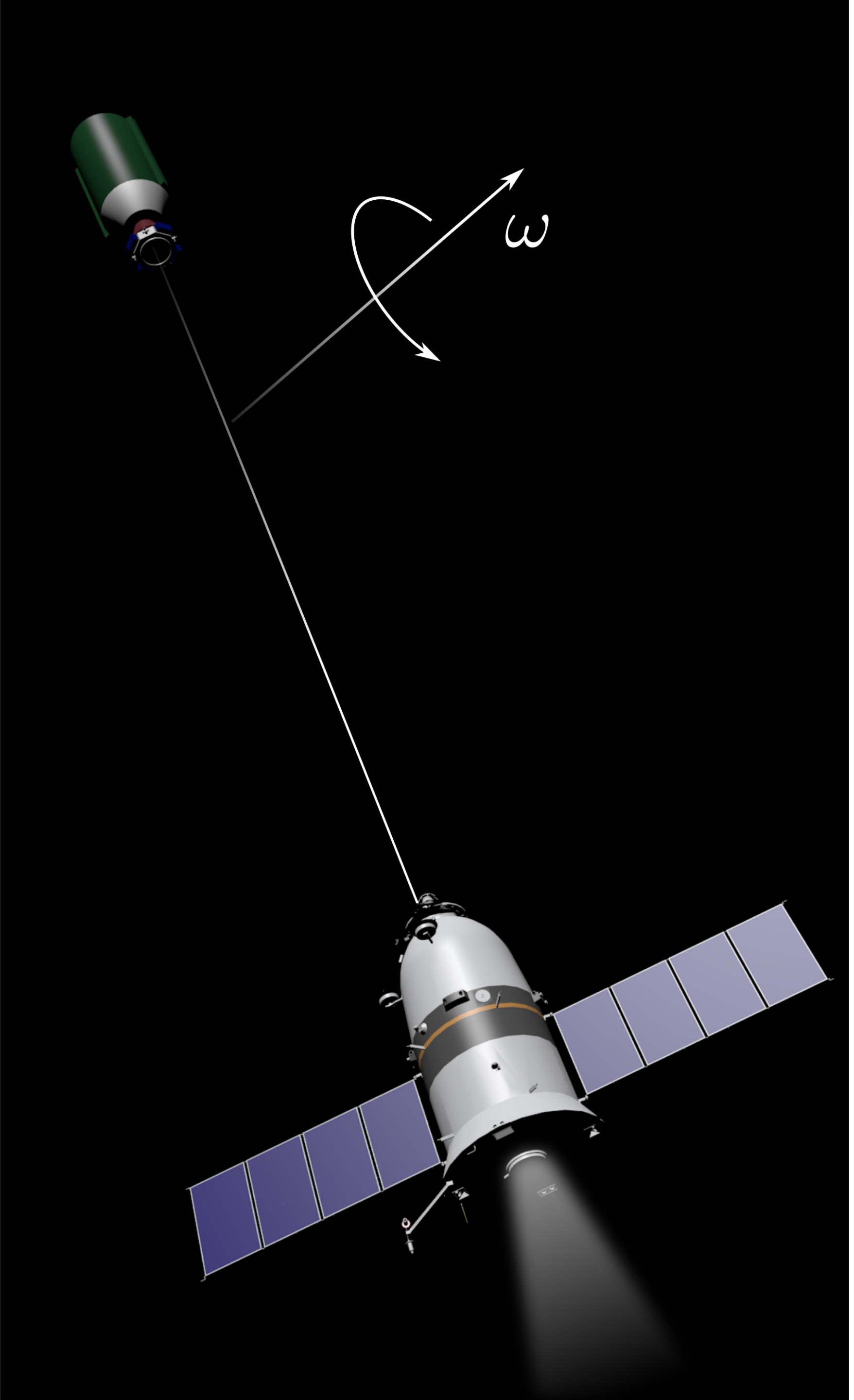



https://youtu.be/SlsS146OirY




# Conclusion

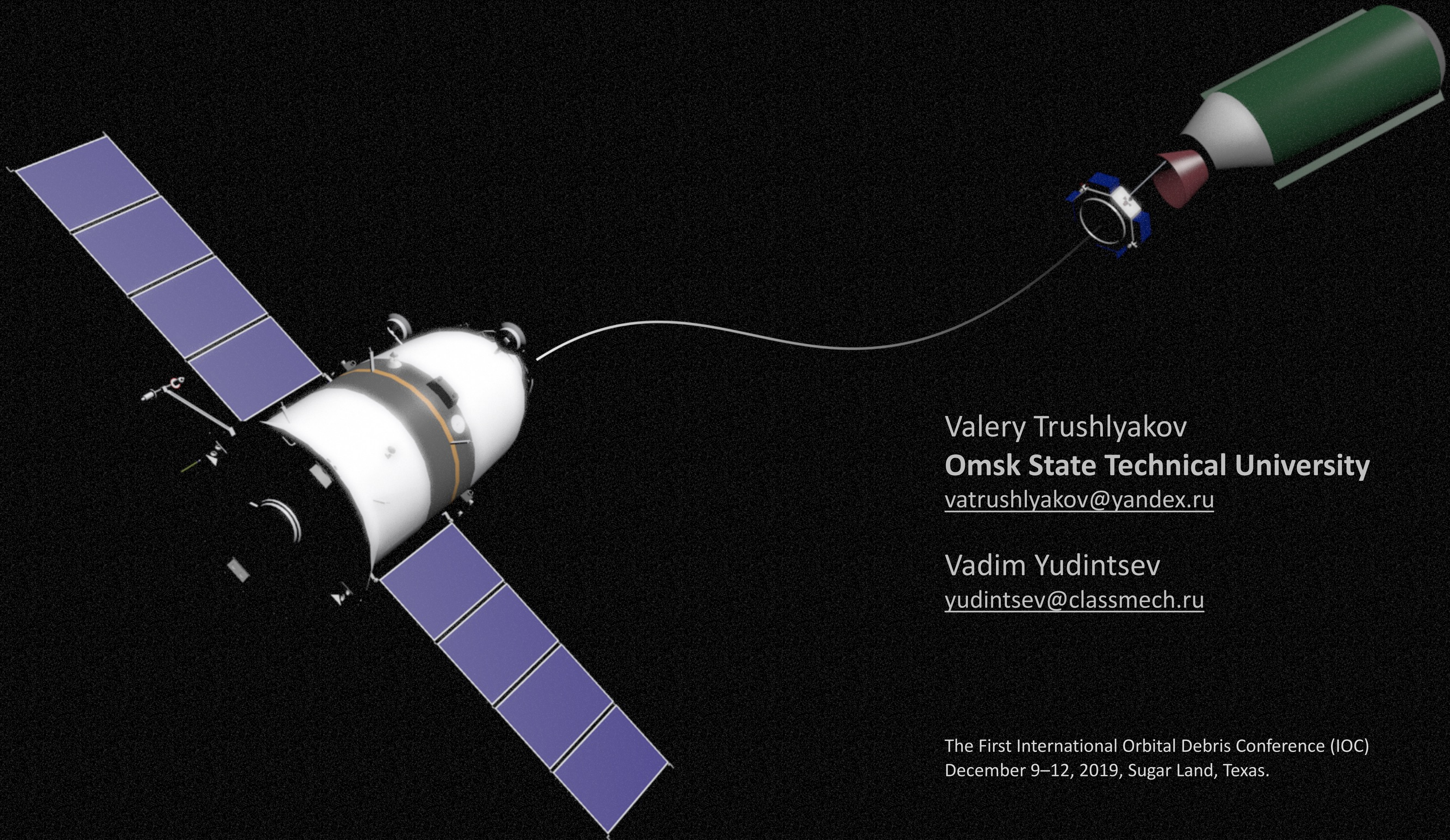
- Rotating tethered tug-debris system doesn’t require hard mechanical interface between the tug and debris
- Rotating tethered tug-debris system can be used to de-orbit of large debris objects using space tug with conventional design
- The space tug can be developed on the base of the existing upper stages or spacecraft (ATV, Briz, Fregat, …)




# TO-DO

Proposal for cooperation

- Analysis of the gripping process and post-capture dynamics of the tethered tug-debris system using various gripping device installed on the autonomous docking module
- Developing attitude control system for the space tug and autonomous docking module (attitude control of the bodies relative to the tether)
- Developing a tether length control algorithm to dump the oscillations of the tug and debris bodies relative to the tether



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