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CubeSat with Dual Robotic Manipulators for Debris Mitigation and Remediation

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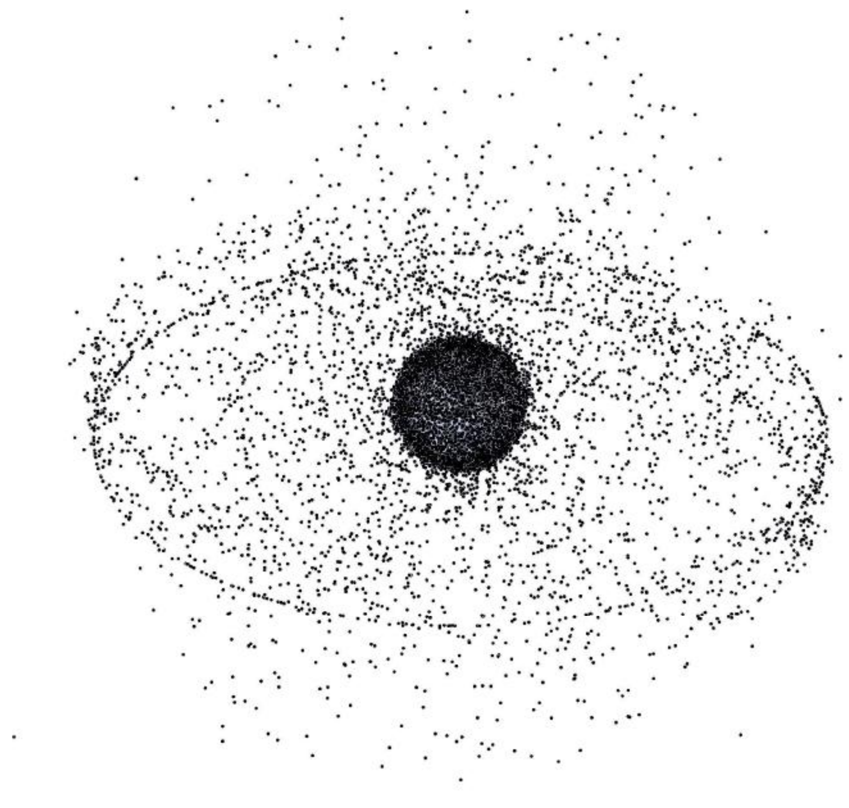
CubeSat with Dual Robotic Manipulators for Debris Mitigation and Remediation

Overview

- Introduction
- Concept of Operations
- Spacecraft Design
- Attitude and Orbital Maneuvers
- Simulation Scenarios
- Results and Discussion
- Conclusions

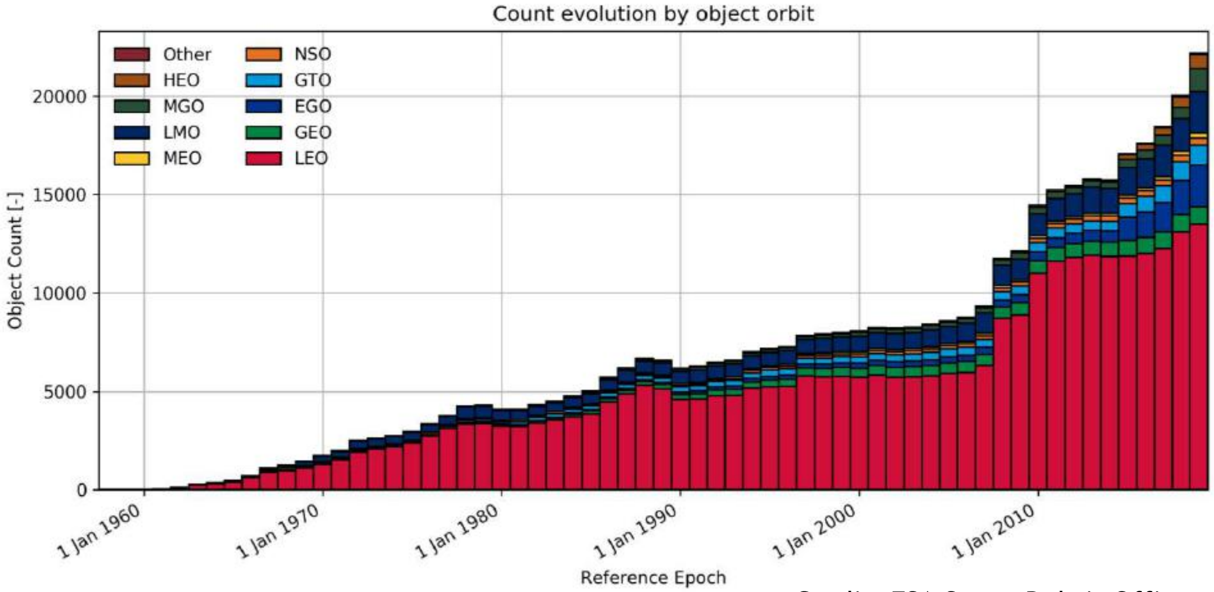


Introduction

- Space manipulators have seen increased usage in orbit for various applications
- Significant increase in objects in orbit, particularly debris items, and interest in human and space asset protection
- Trend towards the miniaturization of spacecraft

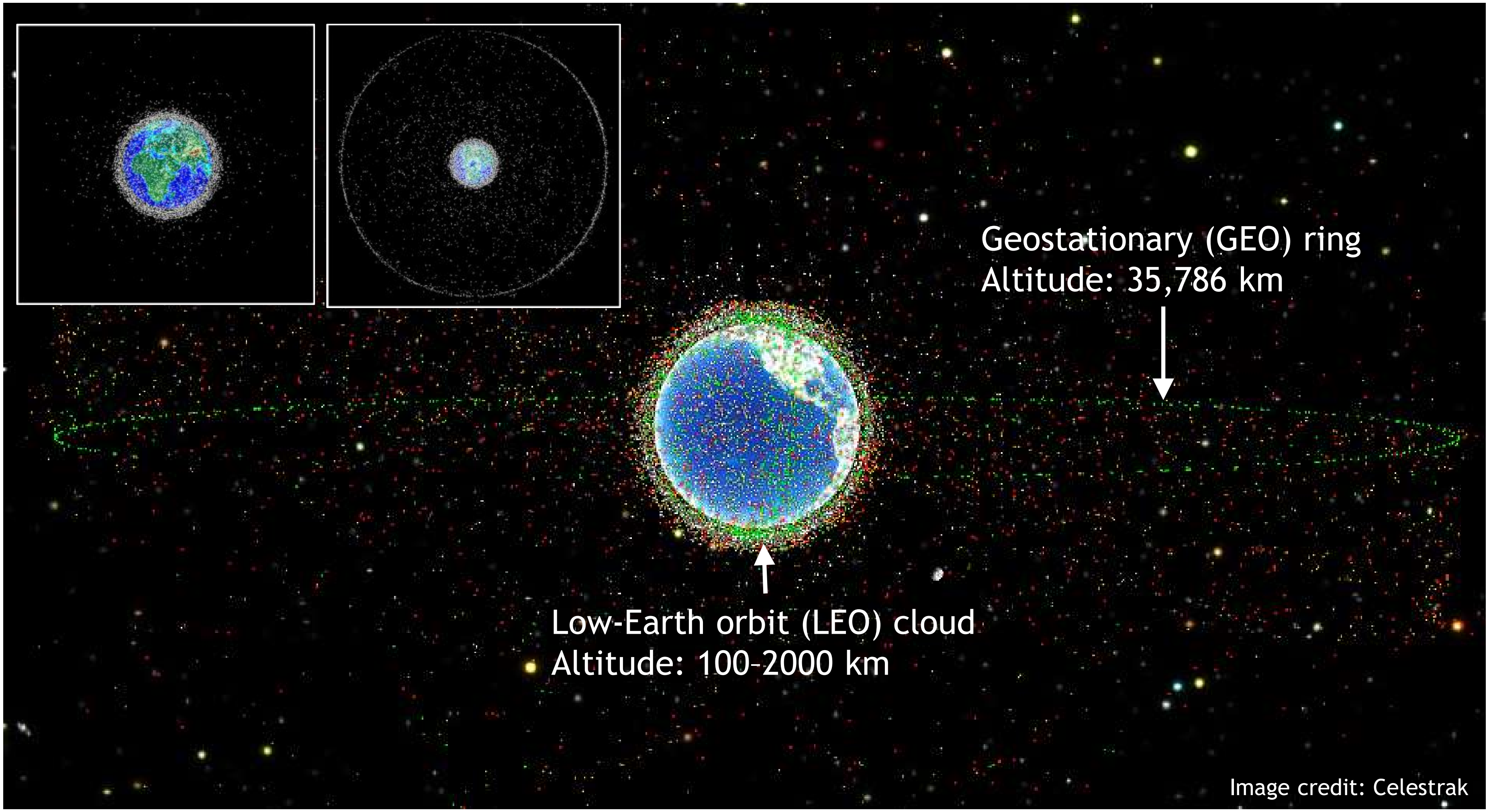
Objective:

- Develop a CubeSat with dual robotic manipulators for debris mitigation and asset protection



Credit: ESA Space Debris Office

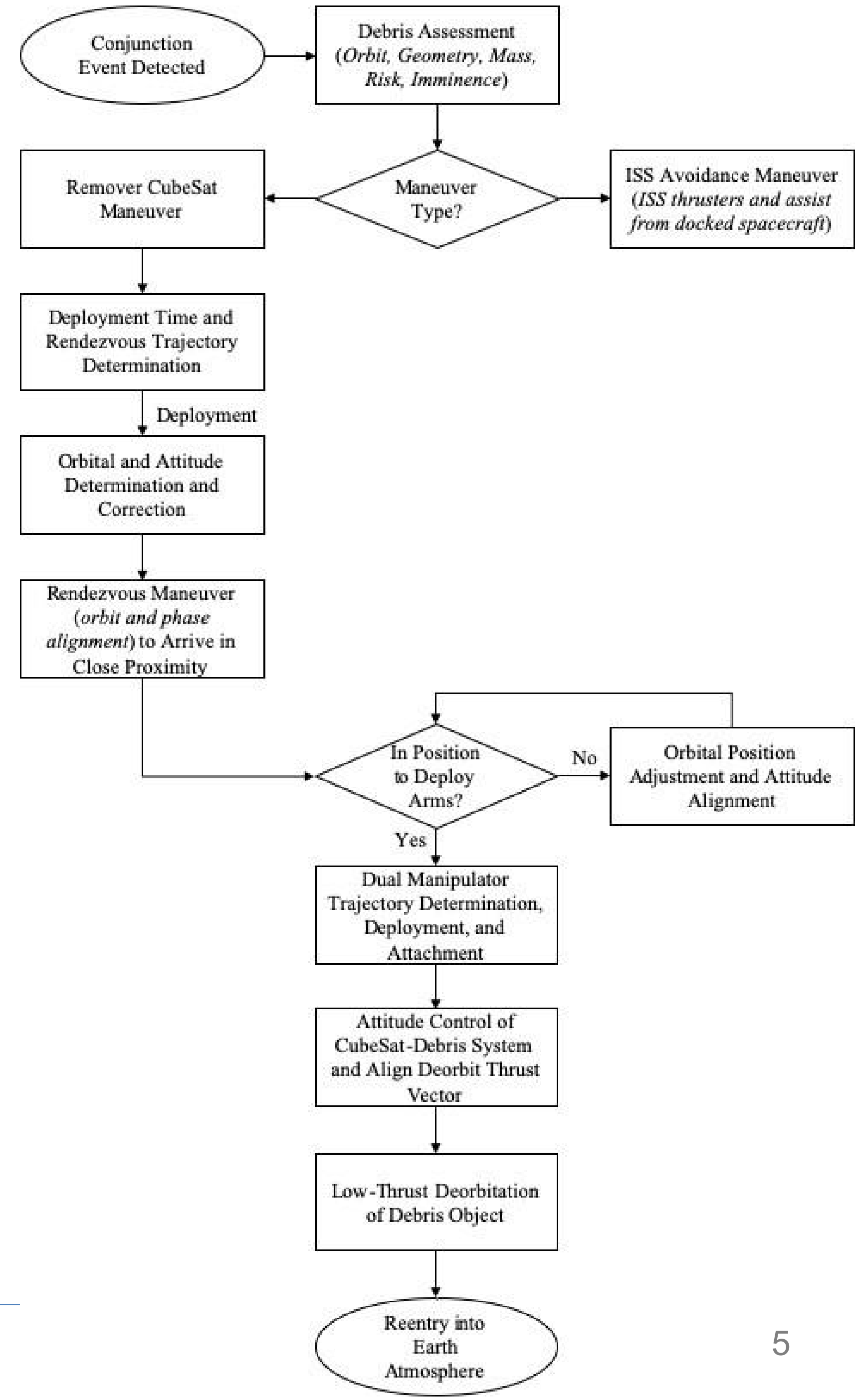
Space Debris Environment



Concept of Operations

Overview of Procedure

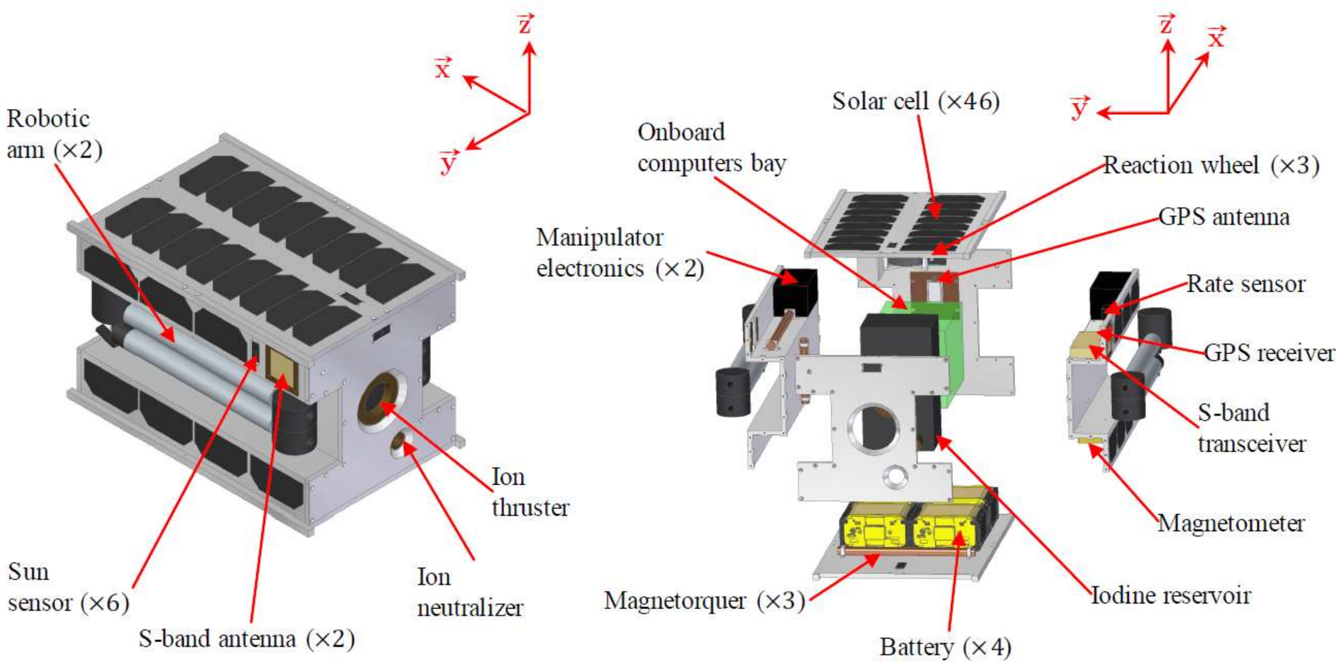
- CubeSats stored onboard space station
- Detection of conjunction event and deployment
- Rendezvous maneuver and attitude alignment
- Arm deployment and capture
- Controlled detumbling and reentry



Spacecraft Design

Specifications

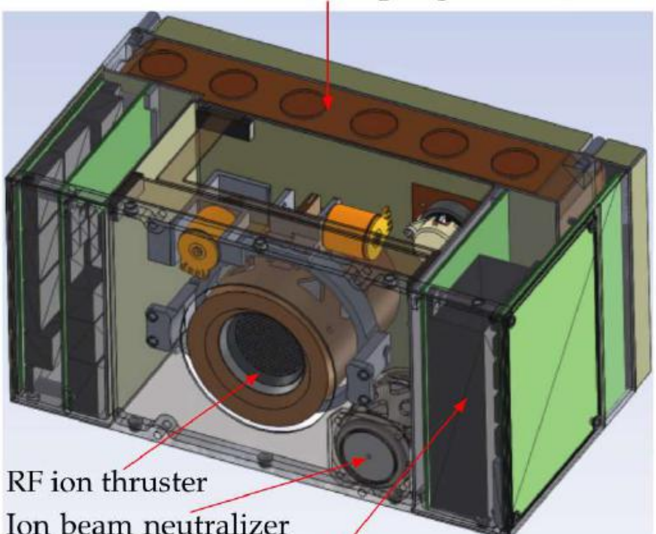
- Primarily designed based on the utilization of commercially available components.
- 12-unit form factor
- 30 × 20 × 20 cm
- 46 solar cells (with 30% efficiency)
- Four battery banks (BM2)



Engineering model of the remover CubeSat (exploded view on the right).

Simulation Specifications

- Key design driver: The type and size of the propulsion system that fits the CubeSat bus.
  - Busek Ion Thruster – 3 cm (BIT-3)
  - 8-kg solid iodine reservoir



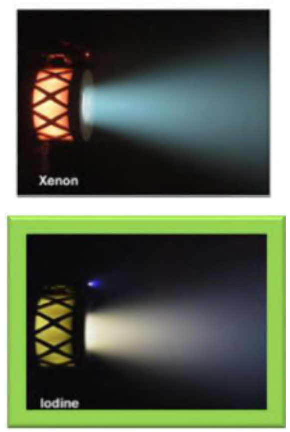
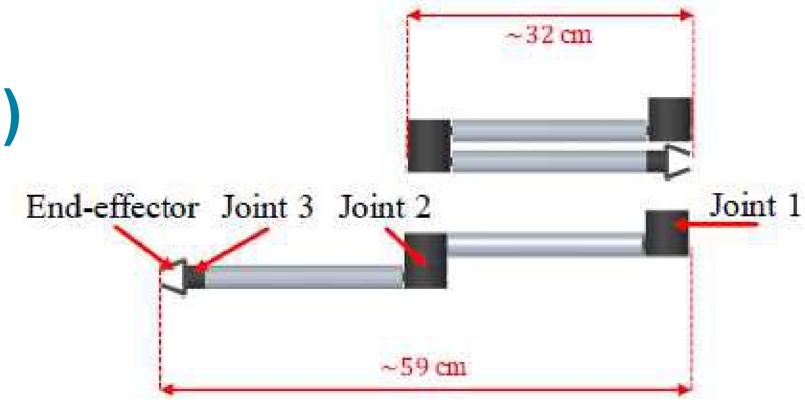


Table 1. BIT-3 technical specifications [14].

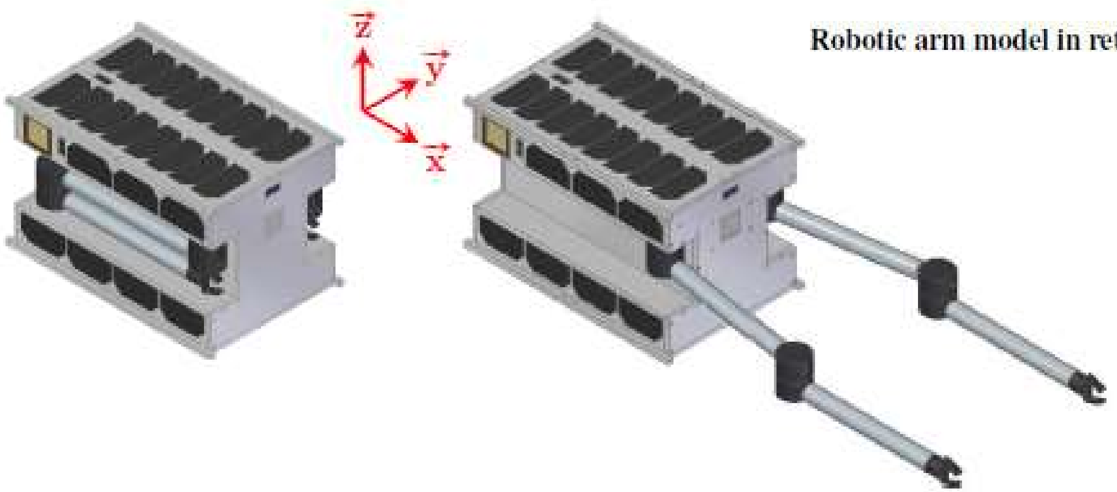
Parameter	Value/Description
Propellant	Iodine, solid storage
System power	56–80 W
Input voltage	28 V (DC)
Propellant mass flow	48 μg/s (nominal)
Thrust	Up to 1.2 mN
Specific impulse (I_{sp})	Up to 2,300 s
Dry mass	1.4 kg (with gimbal) 1.28 (without gimbal)
Integrated gimbal	2-axis, $\pm 10°$

Spacecraft Design

Robotic Manipulators (3 DoF)



Robotic arm model in retracted (top) and extended (bottom) configurations.



Left: Remover CubeSat in the stowed configuration. Right: robotic arm extended.

Spacecraft Design

Mass budget

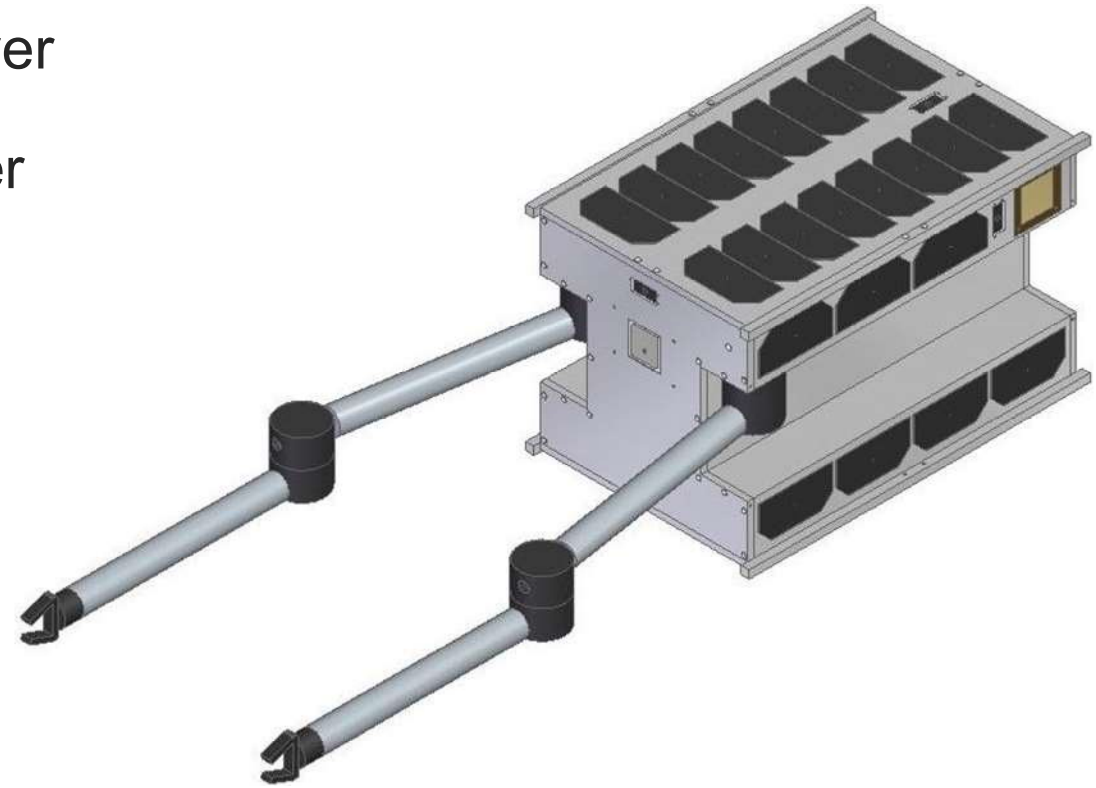
Table 2. Summary of remover CubeSat's mass budget. The mass values include contingencies. References to the components' data sheets are provided.

Subsystem	Mass [kg] (% of total)	Key Components (× Quantity)
Structures	3.51 (18.31%)	Primary structure (obtained from Solid Edge); reaction wheel plate (×1)
ADCS	1.42 (7.41%)	Reaction wheel (×3) [17]; Sun sensor (×5) [18]; magnetometer (×1) [19]; magnetorquer (×3); GPS receiver (×1) [20] and antenna (×1) [21]; computer (×1) [22]
Power	2.25 (11.74%)	Battery (×4) [16]; power board (×1); solar cells (×46) [15]
C&DH	0.10 (0.52%)	House keeping computer [22]
Communications	0.20 (1.04%)	S-band transmitter (×1) [23] and antenna (×2) [23]
Propulsion	9.50 (49.56%)	Ion thruster (×1) [14]; an 8-kg iodine reservoir (×1)
Robotic arm	2.0 (10.43%)	Estimated mass (×2)
Sub-total	18.98 (99.0%)	–
Integration	0.19 (1.0%)	Fasteners and wiring harnesses
Total	19.17 (100%)	
Target	20.00	–
Margin	0.83 (4.33%)	$\text{Margin (\%)} = \frac{\text{Target} - \text{Total}}{\text{Target}} \times 100$

Attitude and Orbital Maneuvers

Subsections:

- Rendezvous maneuver
- Detumbling maneuver
- Deorbiting maneuver
- Disturbance torques
- Orbital perturbations



Attitude and Orbital Maneuvers

Rendezvous Maneuver

Low-thrust trajectory design

- Gauss's variational equations (GVEs) with steering angles

$$\dot{a} = 2\sqrt{\frac{a^3}{\mu}}T\cos\alpha\sin\beta$$

a = semimajor axis

T = specific thrust

α = zimuth steering angle

β = elevation steering angle

μ = gravitational parameter

- Transfer angle between the CubeSat and the debris object

$$\psi = \frac{\mu}{4T}\left(\frac{1}{a_{\mathrm{c}}^2} - \frac{1}{a_{\mathrm{d}}^2}\right)$$

$$\psi = \psi_0 + 2\pi n$$

ψ_0 = transfer angle

n = number of Earth revolutions

$$T = \frac{\mu}{4\psi}\left(\frac{1}{a_{\mathrm{c}}^2} - \frac{1}{a_{\mathrm{d}}^2}\right)$$

Attitude and Orbital Maneuvers

Detumbling Maneuver

- Attitude dynamics

$$\dot{\boldsymbol{\omega}} = \mathbf{I}^{-1}(-\boldsymbol{\omega}^{\times}\mathbf{I}\boldsymbol{\omega} + \boldsymbol{\tau})$$

- Time optimal detumbling torque

$$\boldsymbol{\tau} = -\frac{\mathbf{I}\boldsymbol{\omega}}{\|\mathbf{I}\boldsymbol{\omega}\|}\tau_{\max}$$

- Kinematics of attitude motion

$$\dot{\boldsymbol{\epsilon}} = -\frac{1}{2}\boldsymbol{\omega}^{\times}\boldsymbol{\epsilon} + \frac{1}{2}\eta\boldsymbol{\omega}$$

$$\dot{\eta} = -\frac{1}{2}\boldsymbol{\omega}^{\times}\boldsymbol{\epsilon}$$

Deorbiting Maneuver

- Final decaying orbit

$a_{\mathrm{f}} = R_{\mathrm{e}} + 100\ \mathrm{km}$, where $R_{\mathrm{e}} = 6{,}378\ \mathrm{km}$

- Equations of orbital motion

$$\dot{\mathbf{r}} = \mathbf{v} \qquad \dot{\mathbf{v}} = -\frac{\mu}{r^3}\mathbf{r} + \mathbf{f}_{\mathrm{a}} + \mathbf{f}_{J_2} + \mathbf{T}$$

- Maximum thrust

$$\mathbf{T} = -\frac{1}{m}\frac{\mathbf{v}}{\|\mathbf{v}\|}T_{\max}$$

- Orbit semimajor axis

$$a = \frac{\mu}{2\mathcal{E}} \qquad \mathcal{E} = \frac{\mathbf{v}^{\mathrm{T}}\mathbf{v}}{2} - \frac{\mu}{r}$$

Attitude and Orbital Maneuvers

Disturbance Torques

- Gravity-gradient torque

$$\boldsymbol{\tau}_{\mathrm{gg}} = \frac{3\mu}{r}\mathbf{r}_{\mathrm{b}}^{\times}\mathbf{I}\mathbf{r}_{\mathrm{b}}$$

- Magnetic disturbance torque

$$\boldsymbol{\tau}_{\mathrm{mag}} = -\mathbf{M}_{\mathrm{res}}^{\times}\mathbf{B}_{\mathrm{b}}$$

- Geomagnetic field

$$\mathbf{B}_{\mathrm{b}} = \mathbf{C}_{\mathrm{bi}}\mathbf{B}_{\mathrm{i}}$$

$$\mathrm{B}_{\mathrm{i}} = \begin{bmatrix} (B_r \cos\delta_{\mathrm{dec}} + B_\theta \sin\delta_{\mathrm{dec}})\cos\alpha_{\mathrm{RA}} - B_\phi \sin\alpha_{\mathrm{RA}} \\ (B_r \cos\delta_{\mathrm{dec}} + B_\theta \sin\delta_{\mathrm{dec}})\sin\alpha_{\mathrm{RA}} + B_\phi \cos\alpha_{\mathrm{RA}} \\ B_r \sin\delta_{\mathrm{dec}} - B_\theta \cos\delta_{\mathrm{dec}} \end{bmatrix}$$

Orbital Perturbations

- Atmospheric drag

$$\mathbf{f}_{\mathrm{a}} = \frac{1}{2}\rho_{\mathrm{a}} C_{\mathrm{D}} \frac{A}{m}\|\mathbf{v}\|\mathbf{v}$$

- Gravitational perturbation due to J_2 zonal harmonics coefficient

$$\mathbf{f}_{J_2} = \frac{3\mu J_2 R_{\mathrm{e}}^2}{2r^5}\left(\left(5\frac{\mathbf{r}^{\mathrm{T}}\boldsymbol{z}_{\mathrm{i}}}{r^2} - 1\right)\mathbf{r} - 2\left(\mathbf{r}^{\mathrm{T}}\boldsymbol{z}_{\mathrm{i}}\right)\boldsymbol{z}_{\mathrm{i}}\right)$$

$$\boldsymbol{z}_{\mathrm{i}} = [0 \quad 0 \quad 1]^{\mathrm{T}}$$

Simulation Scenarios

Simulation parameters

- Representative for rocket bodies in the vicinity of ISS
- External disturbances are included into system dynamics
- Coplanar orbit with ISS, with 10 km smaller semimajor axis
- Equations of motion integrated using RK4 method

Table 3. Simulation parameters.

Parameter	Value
m_c	20 kg
m_d	200 kg
A	4 m^2
T	1.25 mN
$\mathbf{M}_{res}$	$[0.1 \quad 0.1 \quad 0.1]^\mathsf{T}$ A·m^2
$\mathbf{I}$	$\begin{bmatrix} 100 & 15 & 7 \\ 15 & 200 & 10 \\ 7 & 10 & 150 \end{bmatrix}$ kg·m^2
$[\epsilon_0^\mathsf{T} \quad \eta_0]$	$[0 \quad 0 \quad 0 \quad 1]$
ω_0	$[0.5 \quad -0.5 \quad -0.5]^\mathsf{T}$ rad/s
$\mathbf{r}_0$	$[-2171 \quad 6420 \quad 0]^\mathsf{T}$ km
$\mathbf{v}_0$	$[-4.50 \quad -1.52 \quad 6.02]^\mathsf{T}$ km/s

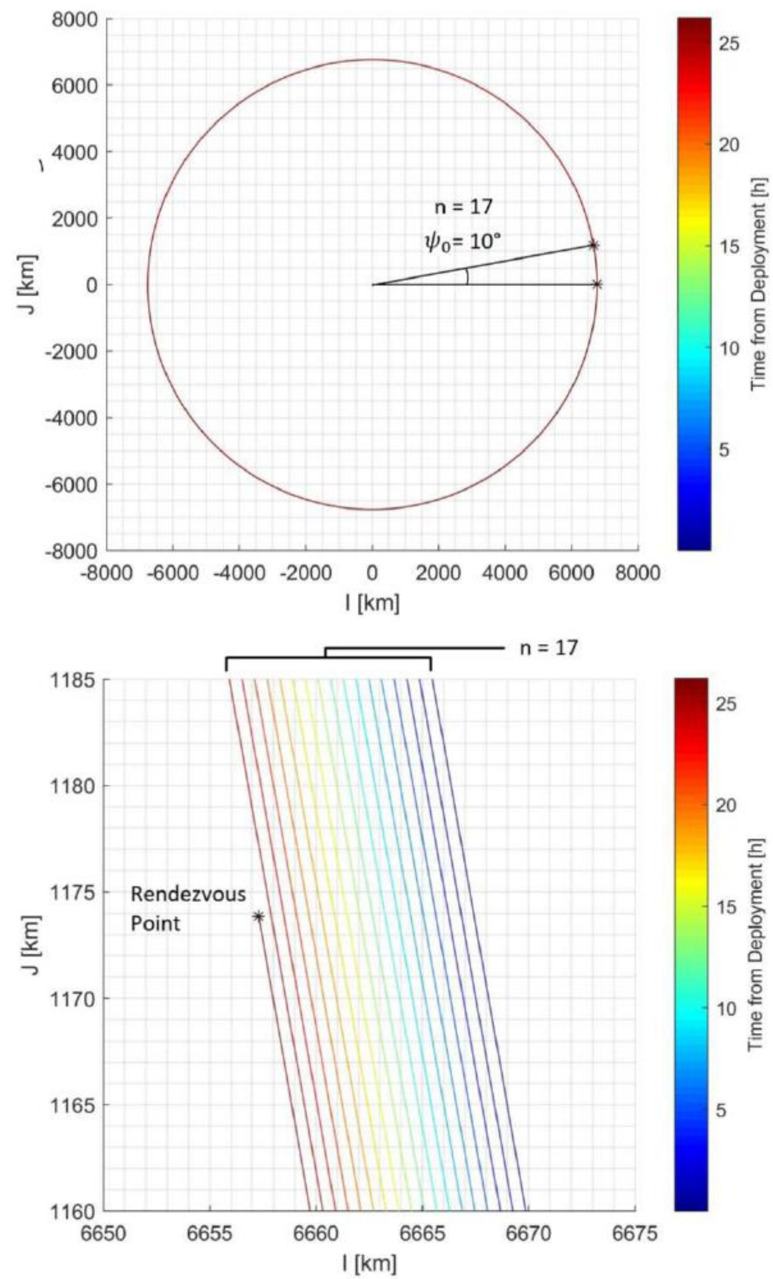
Results

Rendezvous

- Remover CubeSat rendezvous geometry with debris (top)
- Zoomed-in depiction of the rendezvous point of the CubeSat and debris object (bottom)

Maneuver Results

- Initial altitude of debris 390 km
- Transfer angle (ψ_0) is 10 degrees
- Number of revolutions = 17
- Transfer time = 26.2 h
- Fuel consumption = 10.1 g



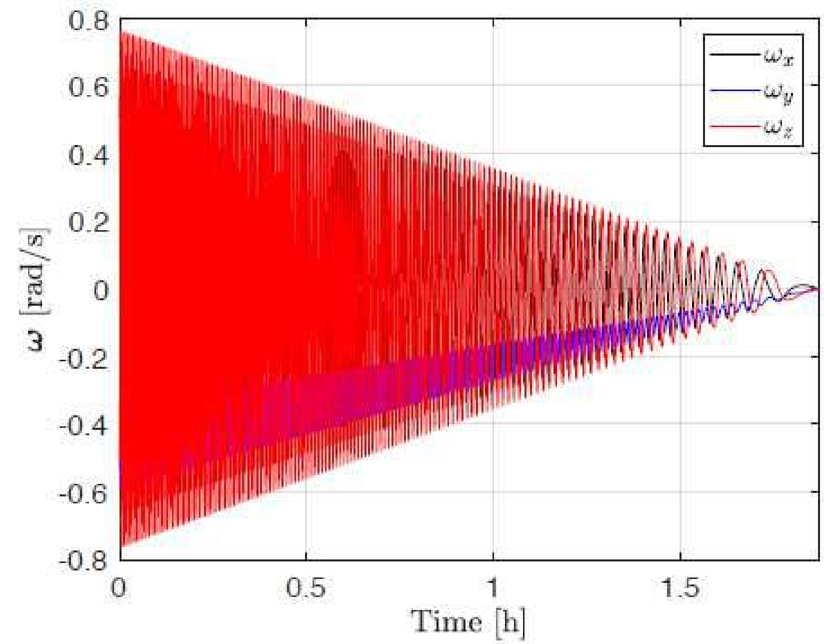
Results

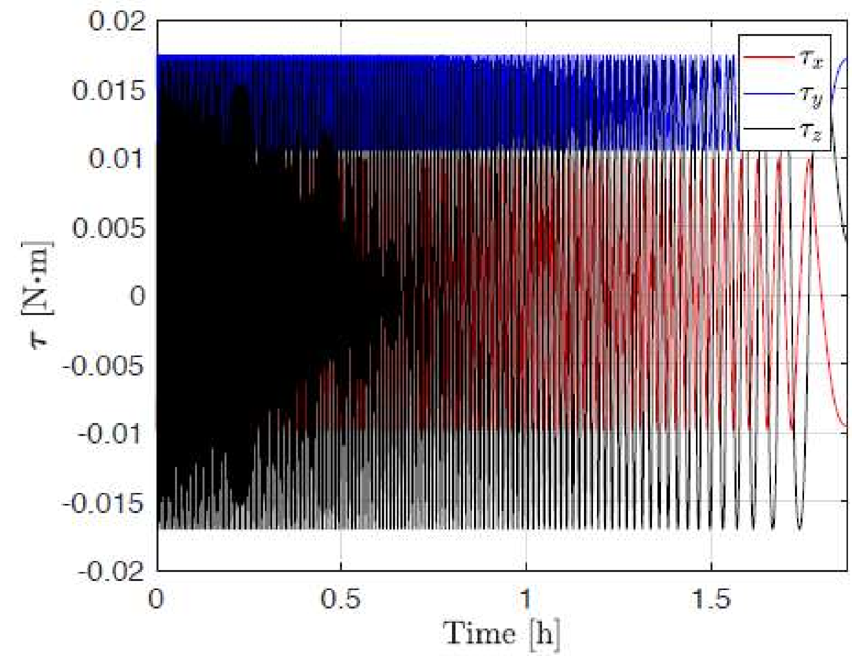
Detumbling

- Time history of the angular velocities during detumbling (top)
- Torque produced during the detumbling maneuver (bottom)

Maneuver Results

- Initial angular velocities ($\boldsymbol{\omega}$) reduced to zero
- Detumbling time = 1.87 h (1h 52 m)
- Maximum allowable torque maintained throughout maneuver (i.e., $20 \times 10^{-3}\ \mathrm{N \cdot m}$)





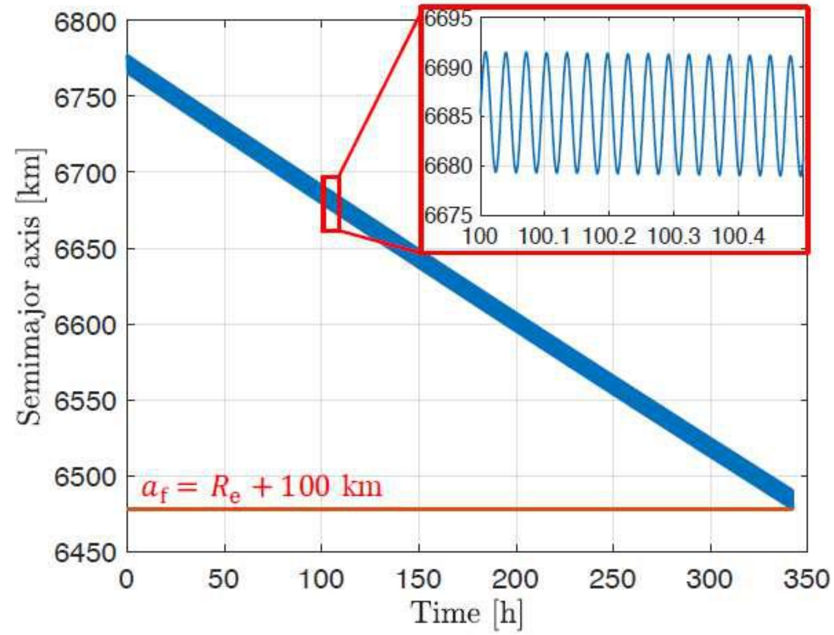
Results

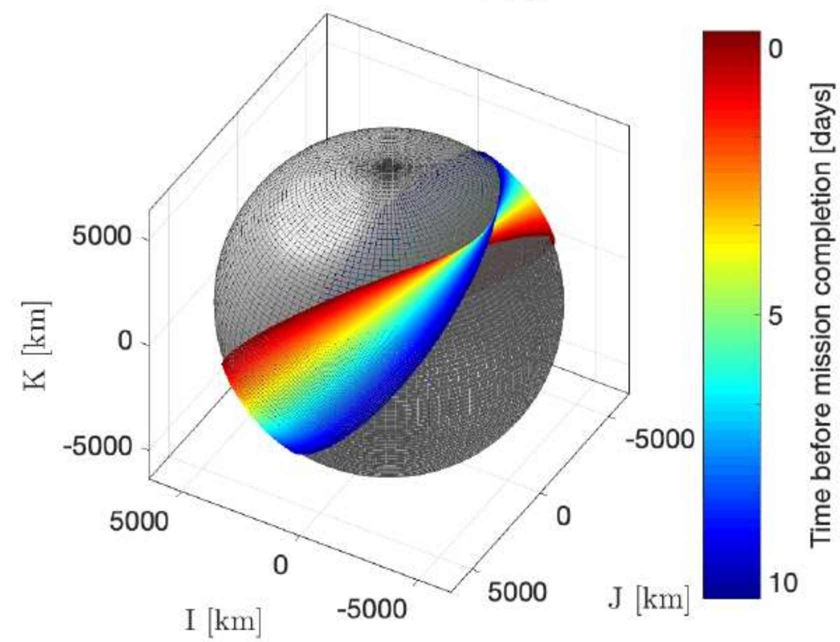
Deorbiting

- Time history of the orbit semimajor axis during deorbiting (top)
- Orbital trajectory of the CubeSat-debris during the last 10 days of the mission (bottom)

Maneuver Results

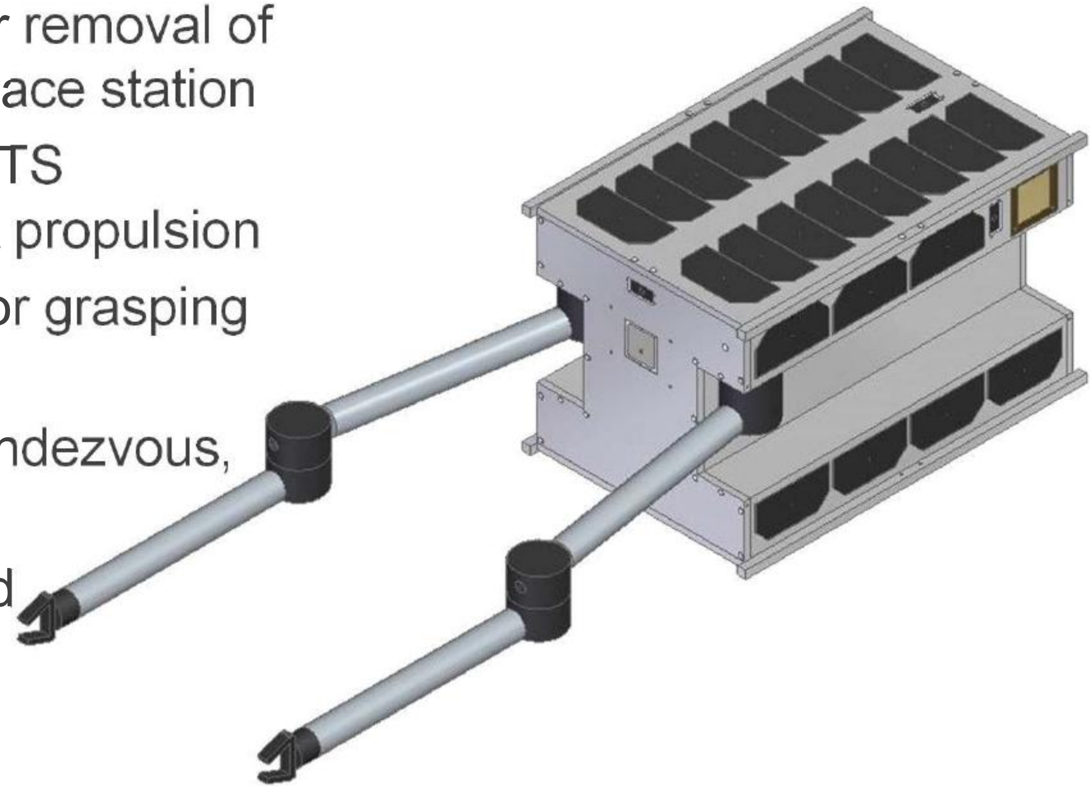
- Sinusoidal pattern attributed to the J_2 perturbations
- Deorbit altitude of 100 km
- Deorbitation time: 340 days
- Fuel consumption: 1.42 kg





Conclusions

- CubeSat-based concept for removal of debris in the vicinity of a space station
- 12-unit form factor with COTS components and low-thrust propulsion
- Two robotic manipulators for grasping debris
- Simulation completed of rendezvous, detumbling, and deorbiting
- Results show feasibility and reduction in debris lifetime



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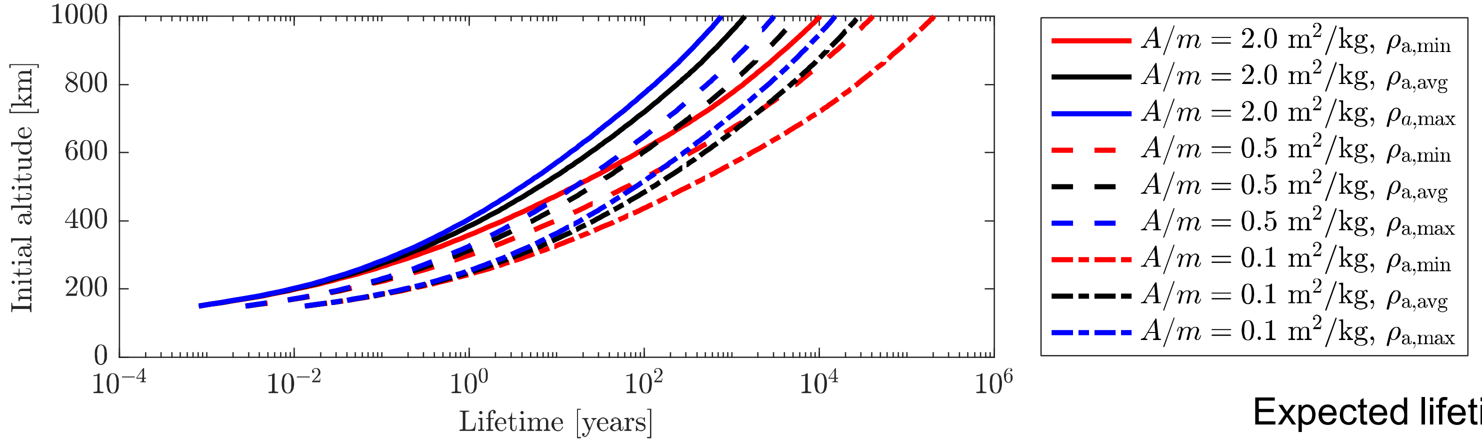
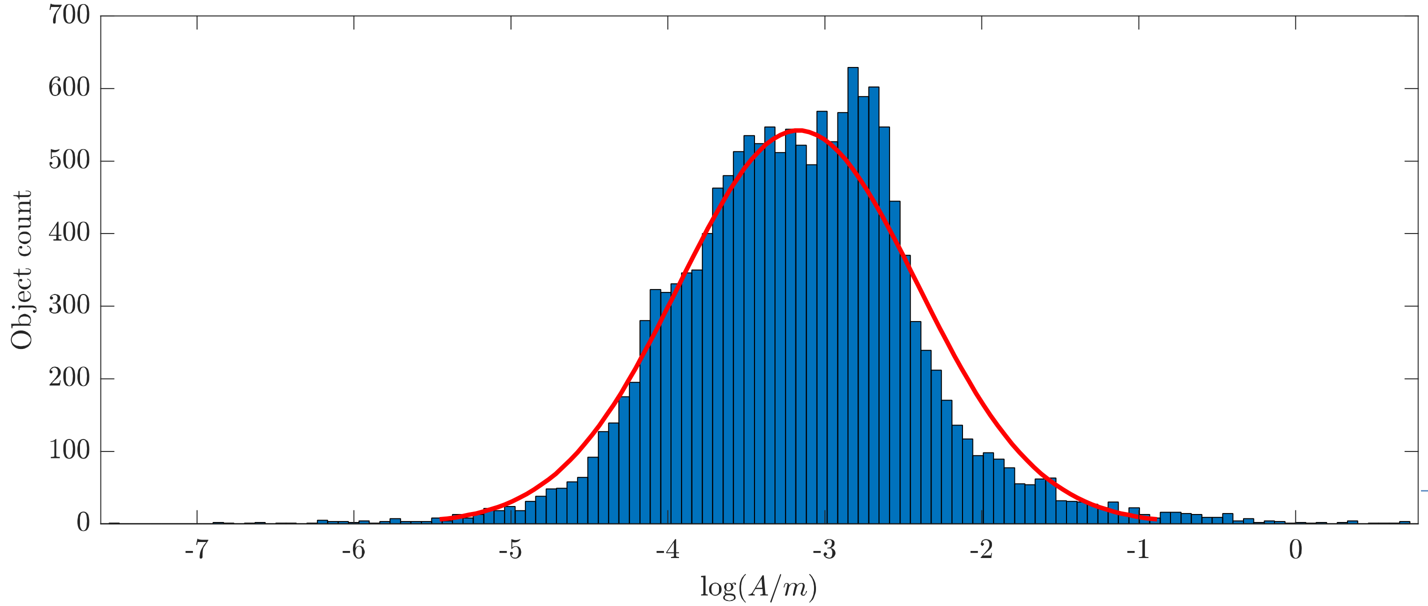
Natural Lifetime of Debris Objects



Expected lifetime of LEO objects



Distribution of area-to-mass ratios of debris objects