Electrodynamic Tether and Brake Sails Combination Deorbit Design

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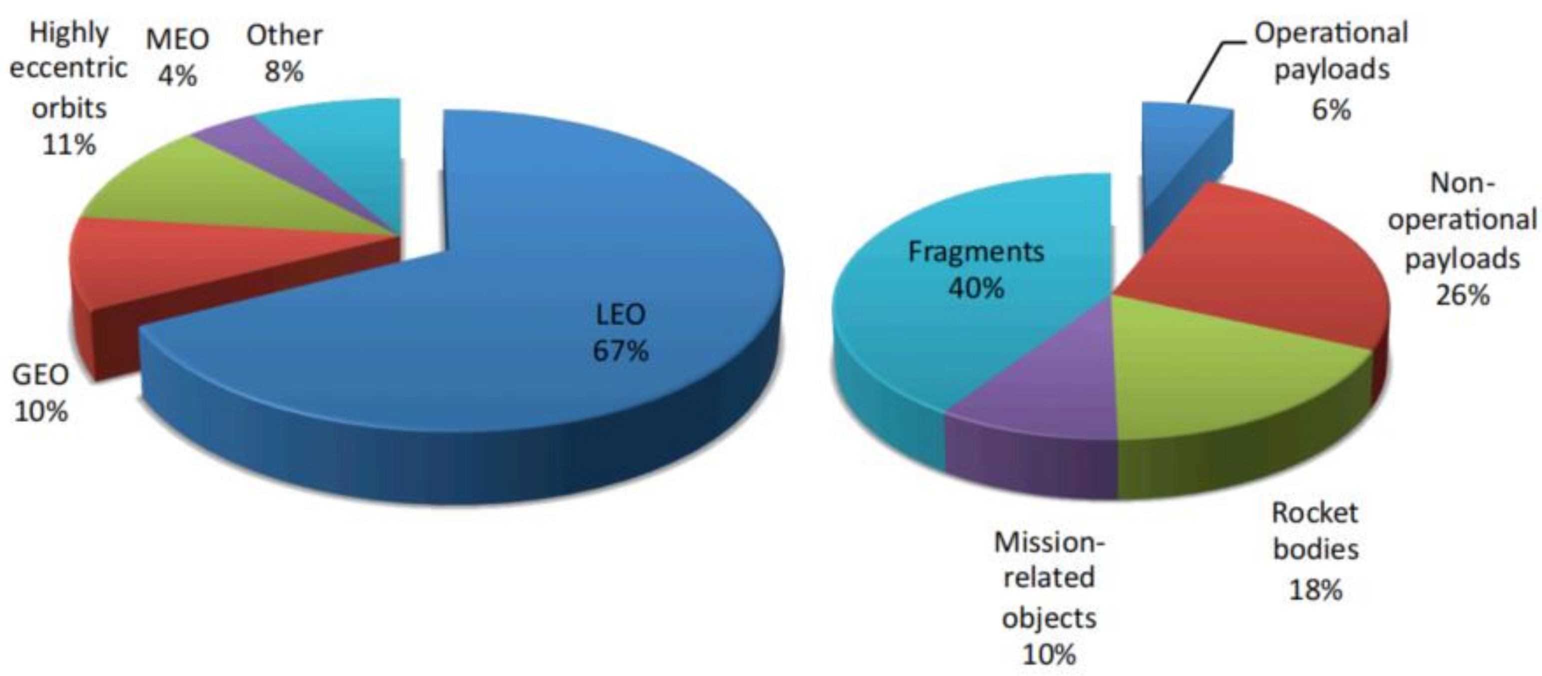
Overview

- **Motivation**
- Tethered Braking Sail Combinations Design
- Experimental Strategy
- Comparative Analysis of Different Deorbit Strategies
- Prospect : Future Work

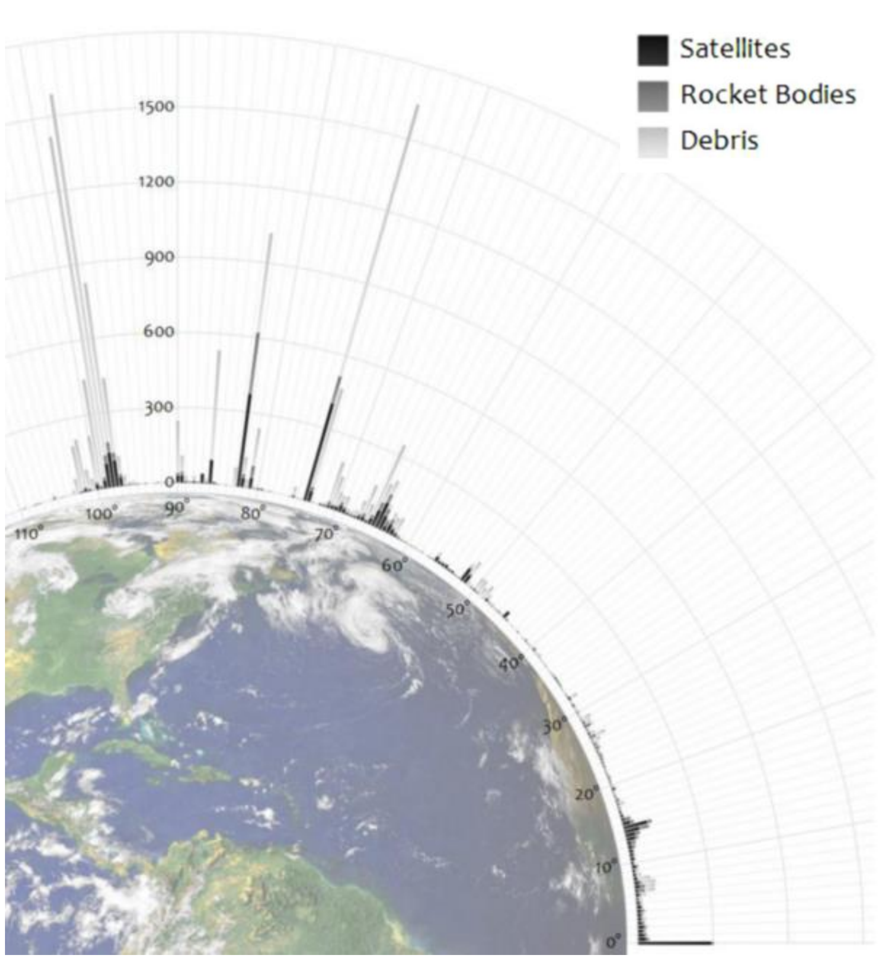
Motivation

ORBITAL DEBRIS CRISIS



Available from: H. Klinkrad, Space Object Catalogs, SSA Conference 15 Sep 2006, Colorado Springs

Distribution of Earth-orbiting objects by orbit (left) and object type (right)



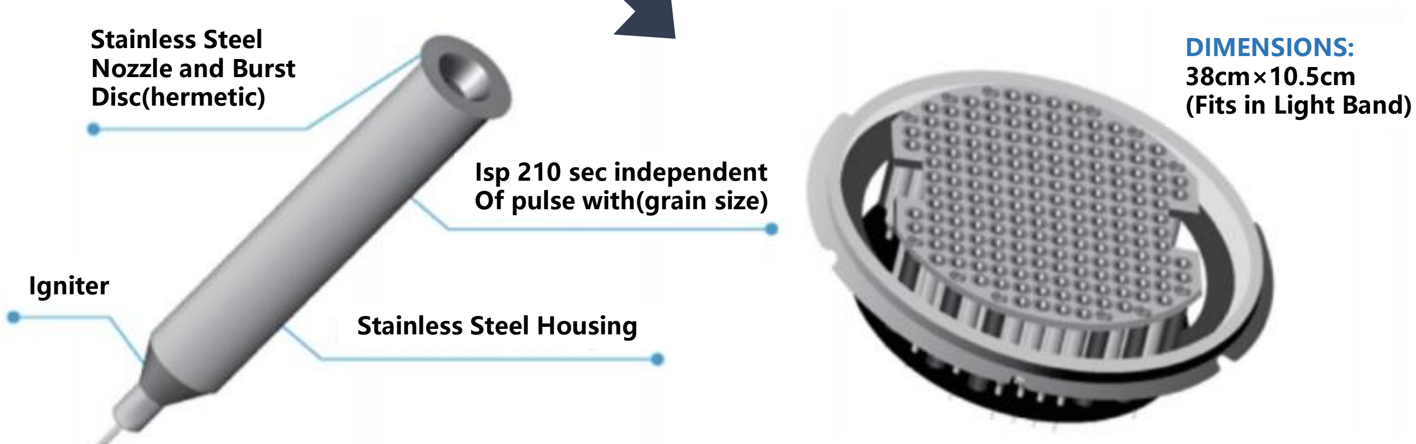
Available from: ⟨https://www.space-track.org/#/ssr⟩, 2014 (accessed 06.01.14).

Distribution of LEO objects per orbit inclination

Motivation

CURRENT DEORBIT STRATEGIES

ACTIVE DEVICES
- Electrical thrusters
- Rockets



Available from:
https://psemc.com/products%20/satellite-propulsion-system/

Pacific Scientific’s SRM and
an example SRM cluster for in-space applications

Available from:
Electric propulsion activities at ESA, in: Proceedings of 31st International Electric Propulsion Conference, 20–24 Sept. 2009, IEPC 2009–237.

Artisti view of
the Bepi-Colombo spacecraft

- **FUEL CONSUMPTION**
- **COMPLEX CONTROL**

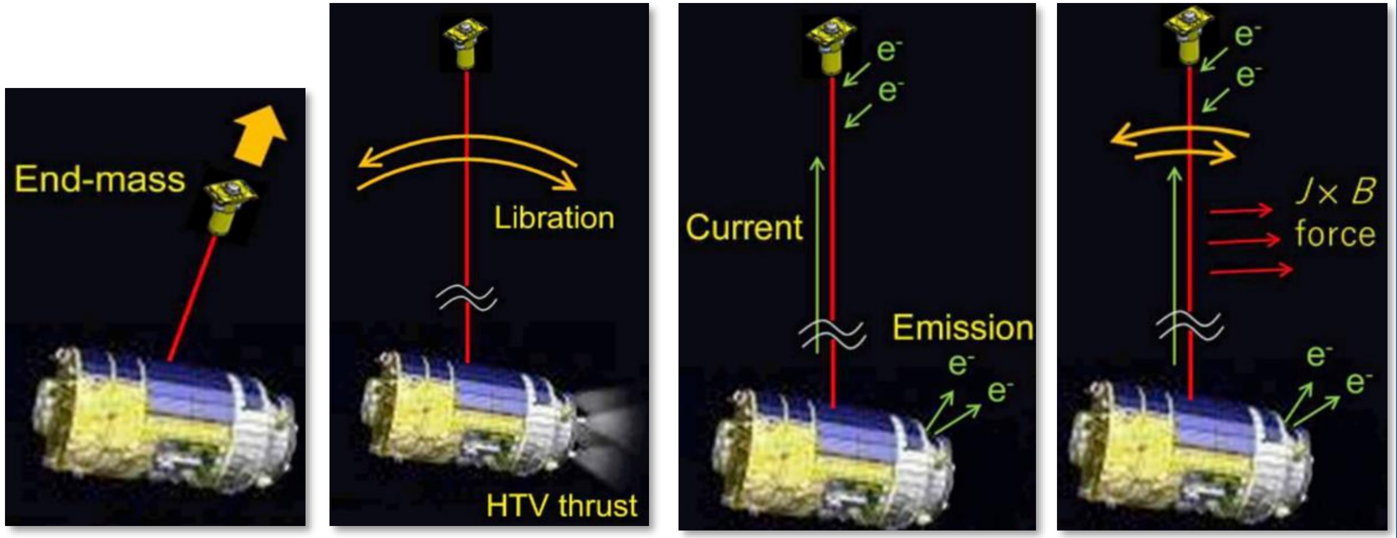
Motivation

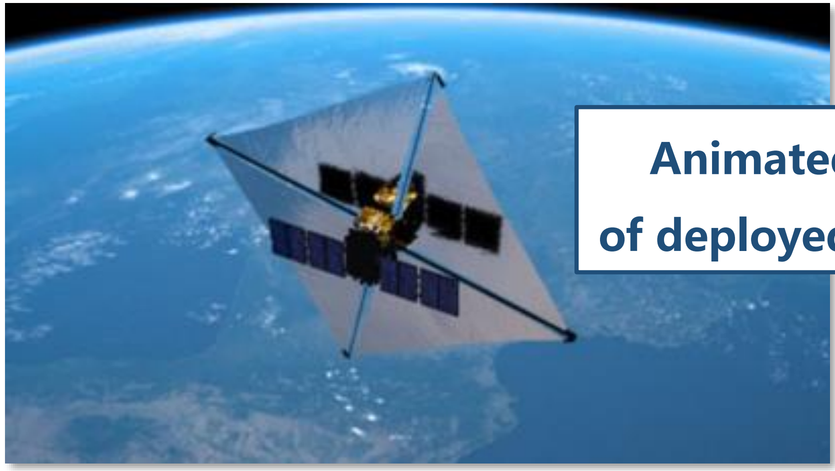
CURRENT DEORBIT STRATEGIES

PASSIVE TECHNOLOGIES
- Drag augmentation
- Electrodynamic tethers

Available from:
Review of KITE – Electrodynamic tether experiment on the H-II Transfer Vehicle.

Experimental events planned in KITE





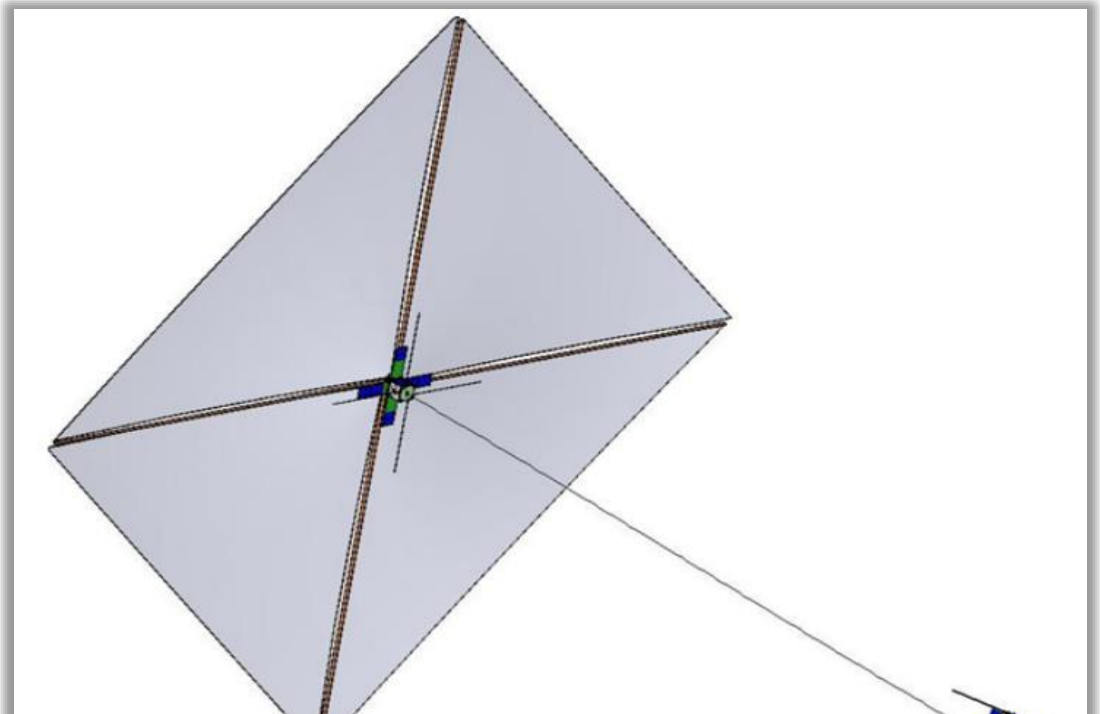
Animated view of deployed ADEO-L

ADEO-N during parabolic fight in August 2019

Available from:
ADEO: the European commercial passive de-orbit subsystem family enabling space debris mitigation. CEAS Space J 13, 591–598 (2021).

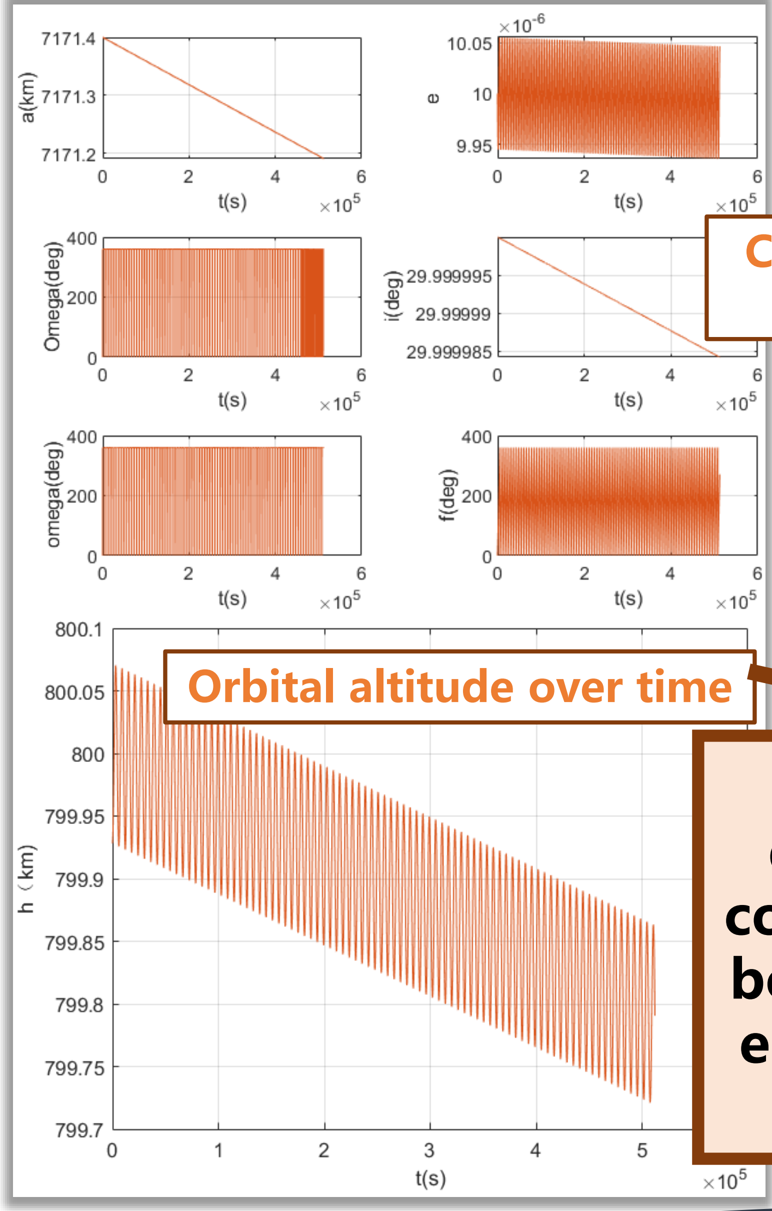
Motivation

FEASIBILITY ANALYSIS



Available from:
Hybrid Solar Sails for Active Debris Removal

Hybrid system of
braking panels and electric tether
to expand the structure



Orbital altitude over time

Changes in the six elements of the orbit over time

A combined body deorbiting strategy combining the roles of both braking sails and electrodynamic ropes is *FEASIBLE*

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Tethered Braking Sail Combinations Design

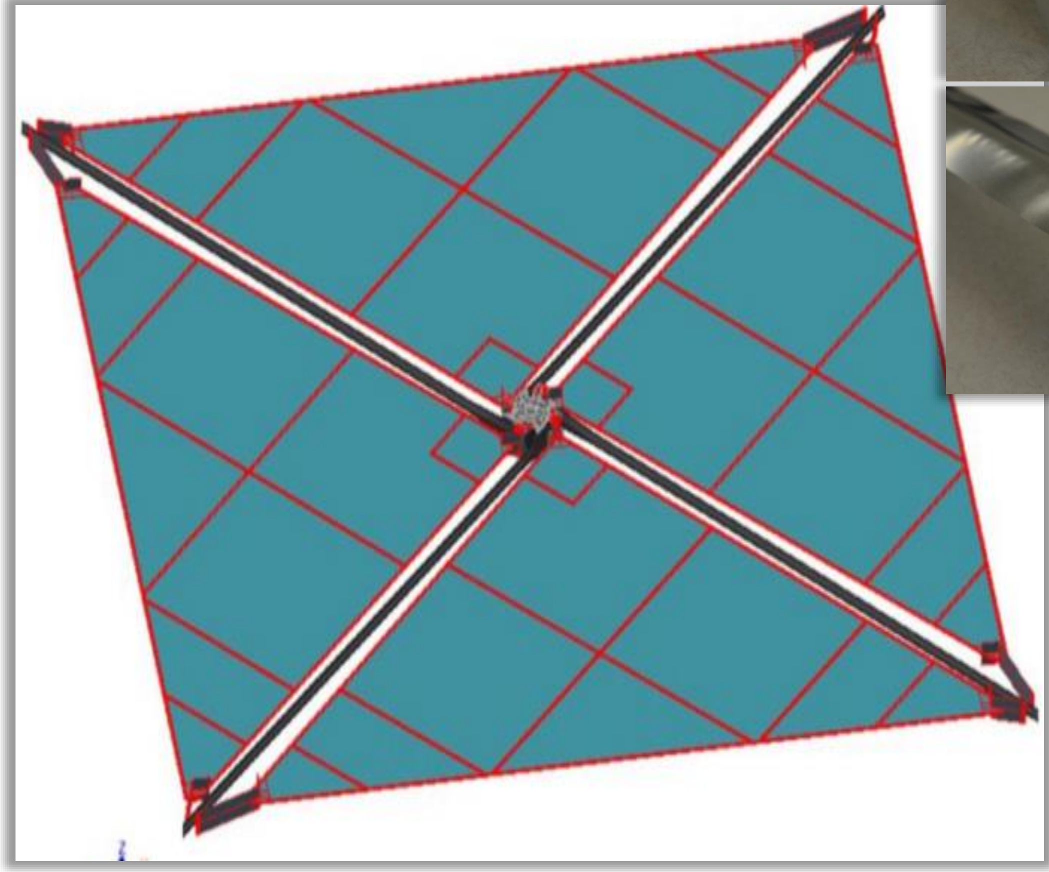
EXTERIOR DESIGN

Parameters	Values
Mass of satellite	5.0kg
Mass of sail	5.0kg
Tether length	10^0.5m
Tether diameter	0.0005m
Orbit altitudes	250-1000km
Orbit inclination	0°-90°

- Combination
- Low price
- High efficiency
- Easy operation
- Large operating space

Tethered Braking Sail Combinations Design

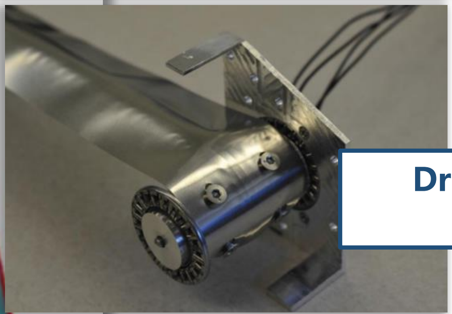
EXTERIOR DESIGN



ADEO-L Deployed confguration with crackstoppers

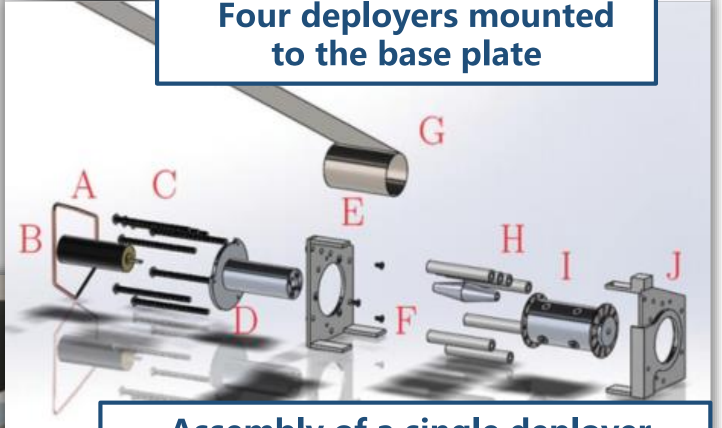
Boom secured to drum

Sleeve attached to motor for later mounting



Drum placed over sleeve

Four deployers mounted to the base plate



Assembly of a single deployer

ADEO-L Engineering Model during deployment testing in 2019

Borrow from to illustrate: 《ADEO: the European commercial passive de-orbit subsystem family enabling space debris mitigation》 & 《Drag Deorbit Device: A New Standard Reentry Actuator for CubeSats》

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Experimental Strategy

ORBITAL DYNAMIC MOTION OF THE SYSTEM

The equation of motion can be written in the form of Gaussian perturbation equations

$$\frac{d\vartheta_j}{dt} = f_j\left(\vartheta_1, \vartheta_2, \vartheta_3, \vartheta_4, \vartheta_5, \vartheta_6, \sigma_x, \sigma_y, \sigma_z\right), \quad j = 1, 2 \ldots, 6$$

the three orthogonal components of spacecraft acceleration resulting from space environmental perturbations in an orbital plane coordinate system

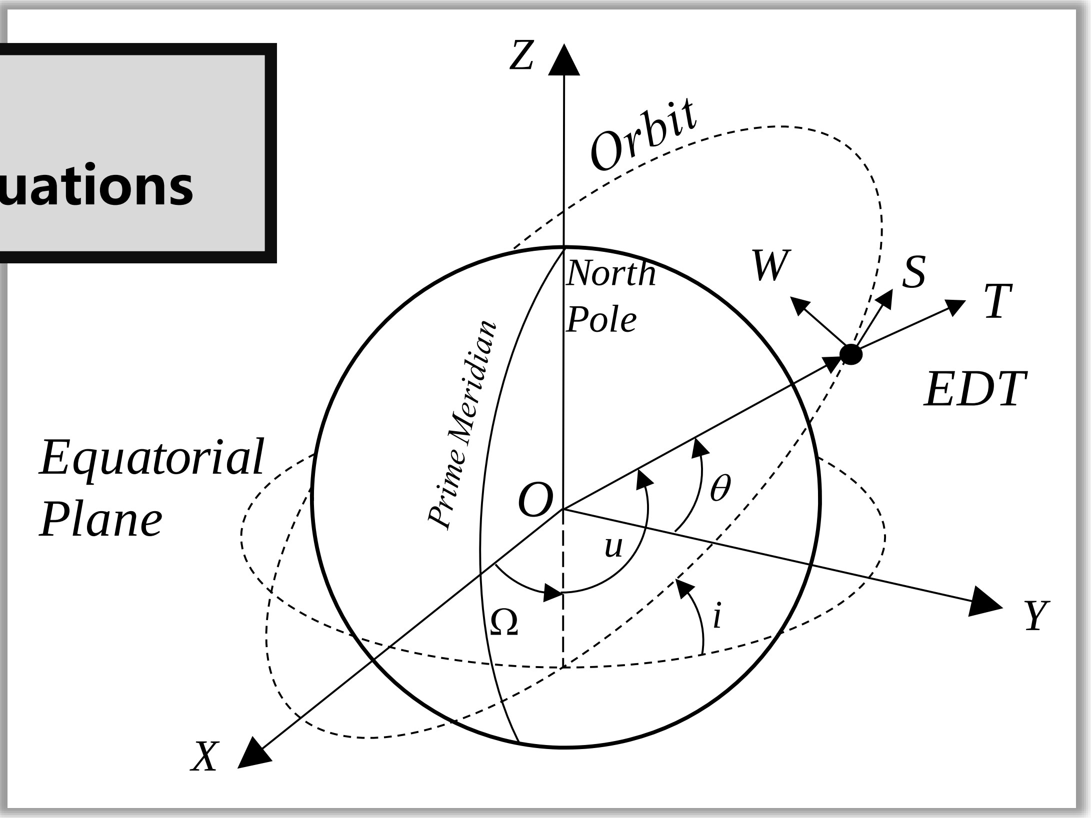


Illustration of system coordinates for orbital motion

Experimental Strategy

LIBRATION MOTION AND ATTITUDE DYNAMICS AND KINEMATICS

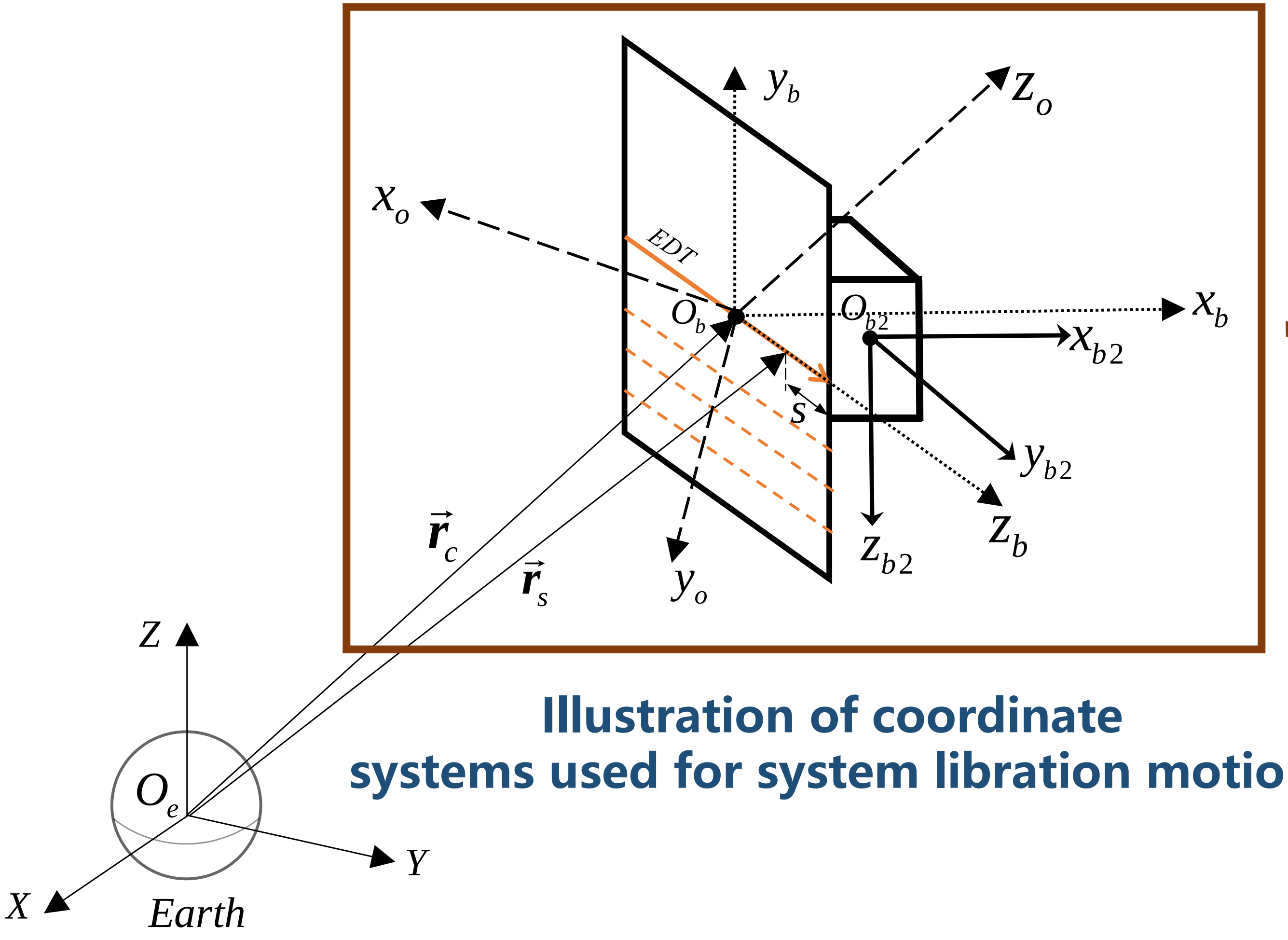
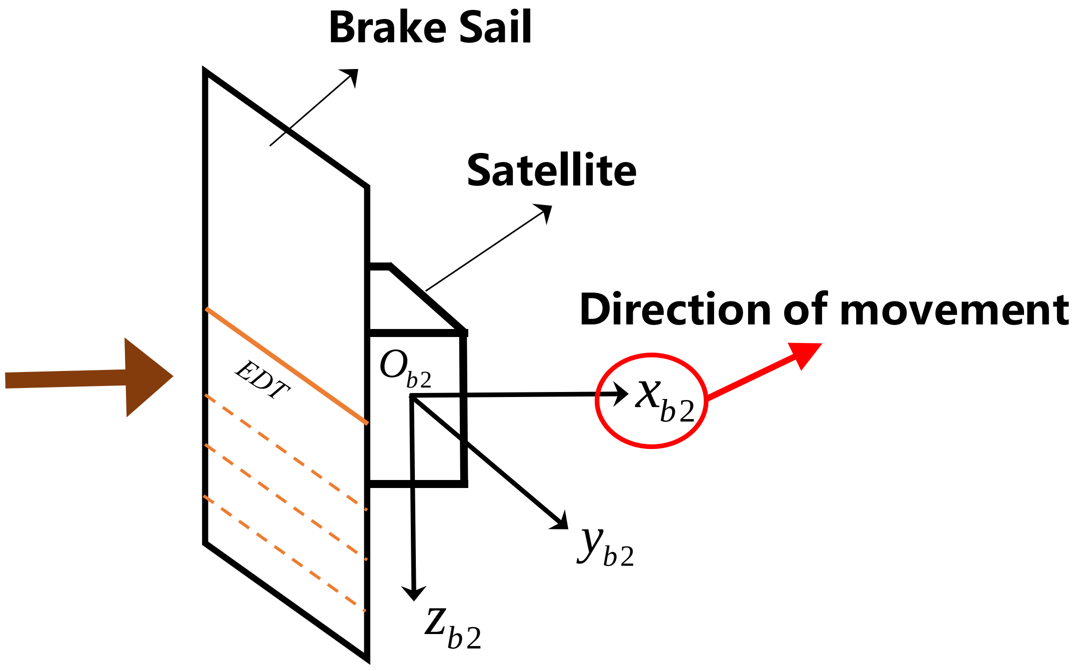


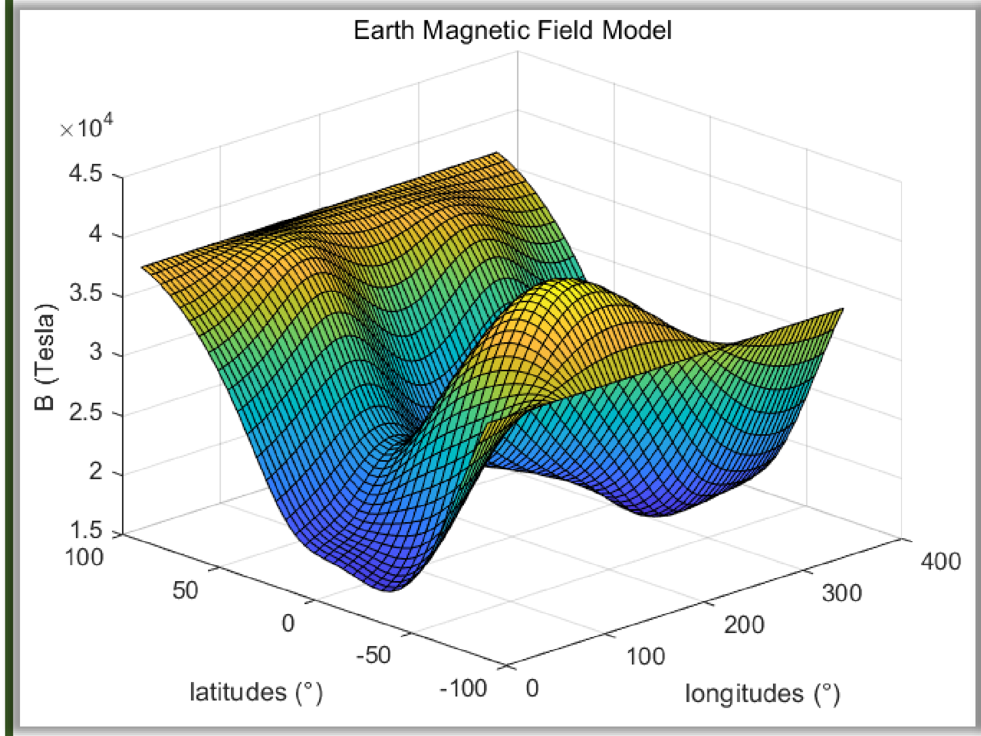
Illustration of coordinate systems used for system libration motion

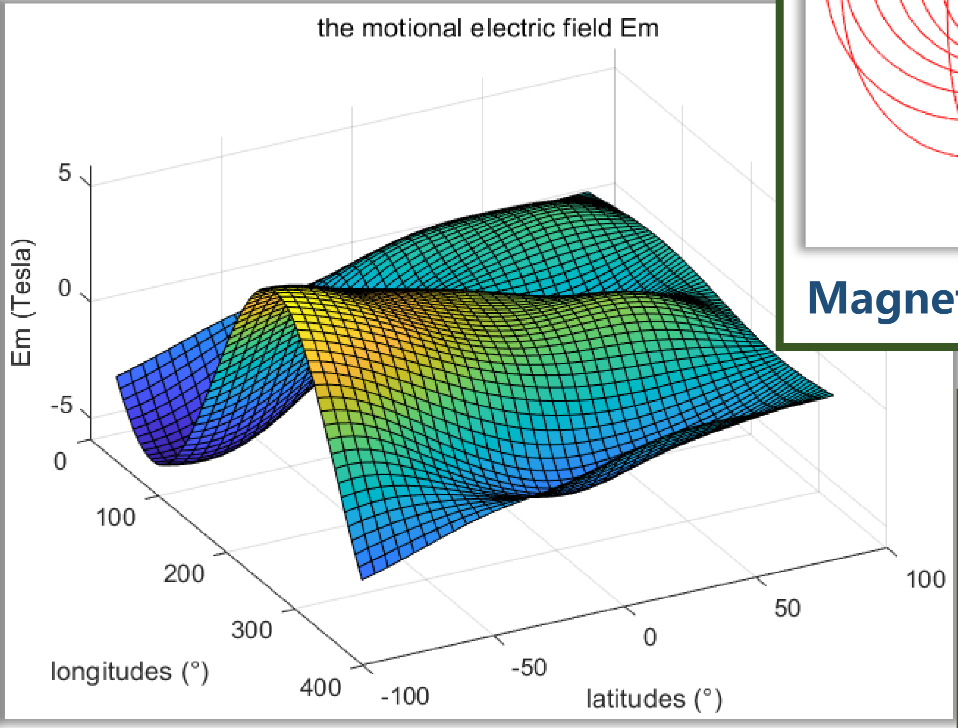


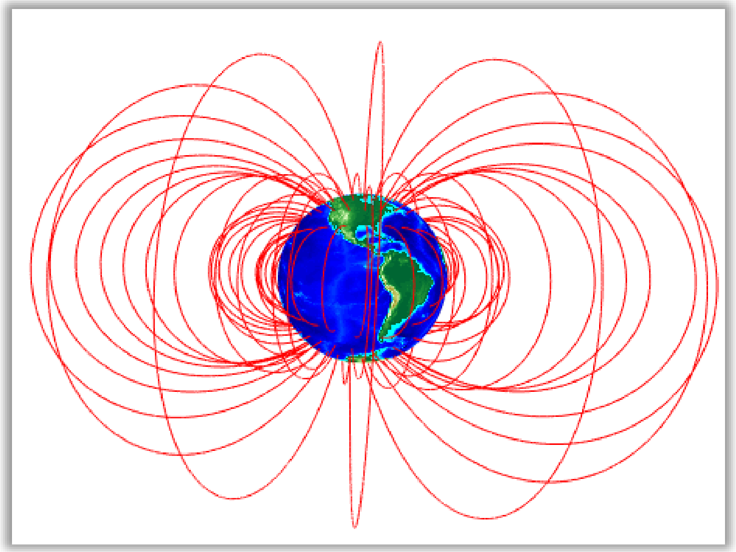
The equation of libration of the system is derived by a straightforward application of Lagrange’ s equation

Experimental Strategy

HIGHER-ORDER GEOMAGNETIC FIELD MODEL (IGRF 2000)







Magnetic Field Line Visualization

As an EDT crosses through the geomagnetic field, a motional electric field is induced

Track altitude 1000km: E_m view along the direction of the EDT

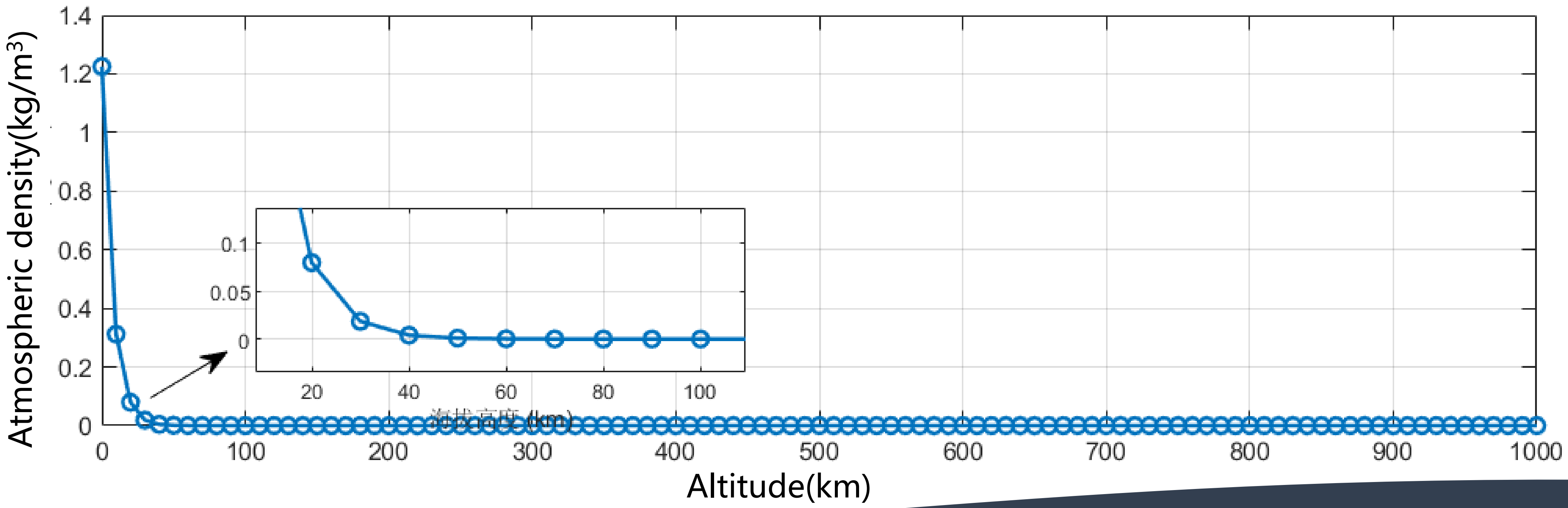
Experimental Strategy

ATMOSPHERIC RESISTANCE

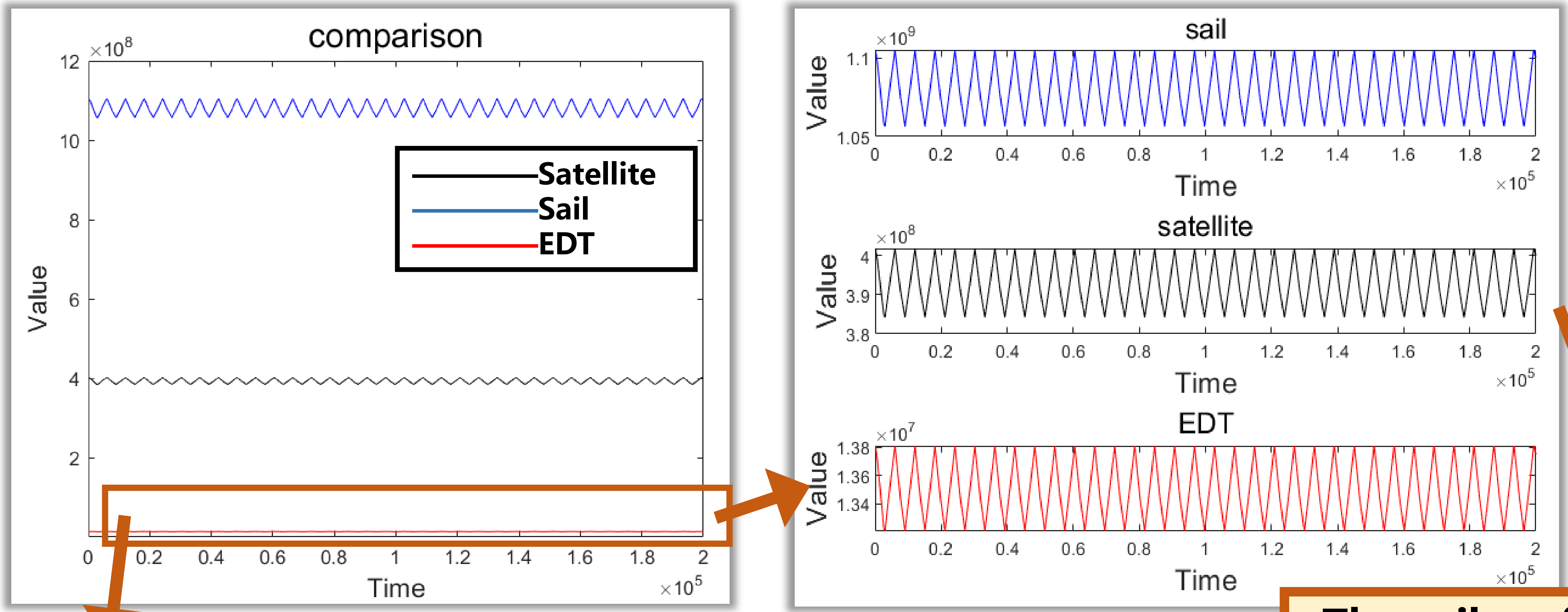
$$h_g = r - r_{po}\left(1 - e_E^2 \cos^2\theta\right)^{-1/2}$$

The geodetic altitude instead of geocentric altitude should be used in the evaluation of the environmental parameters for the sack of accuracy

The relationship between atmospheric density and altitude



ATMOSPHERIC RESISTANCE



Also oscillating just on a smaller scale

Comparison of atmospheric drag acting on braking sail, satellite and electrodynamic tethers

The sail surface is the main object of atmospheric drag

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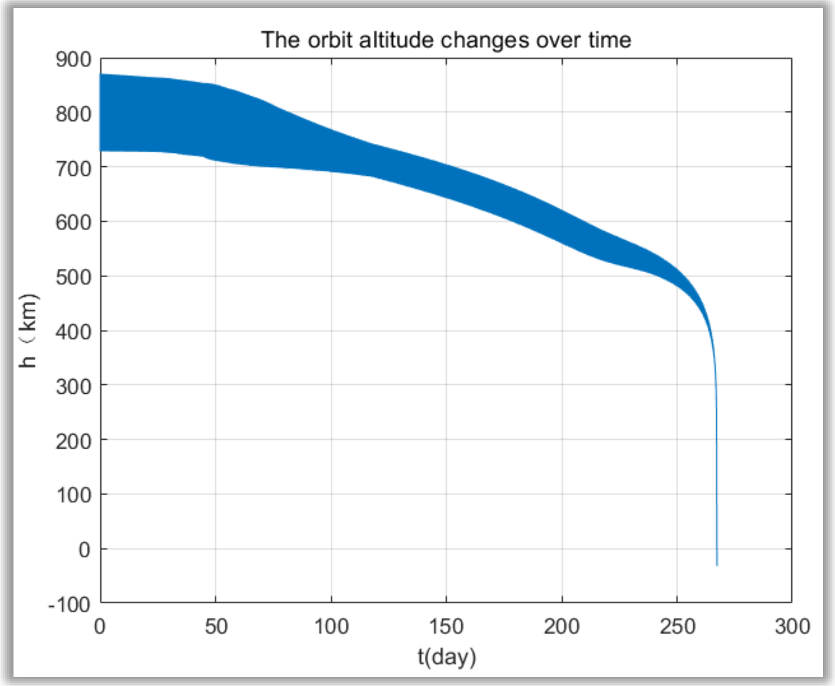
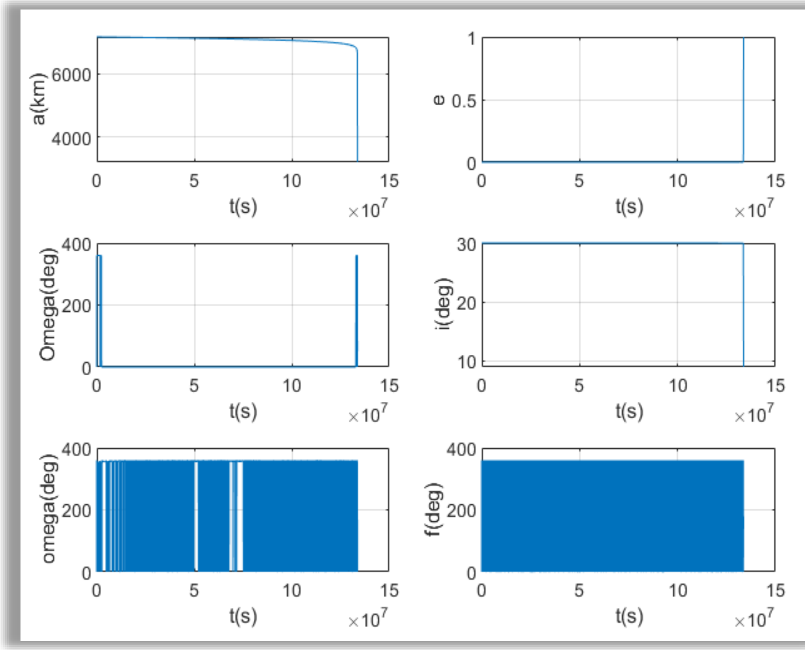
Comparative Analysis of Different Deorbit Strategies

➢ SINGLE-TETHER STRATEGY

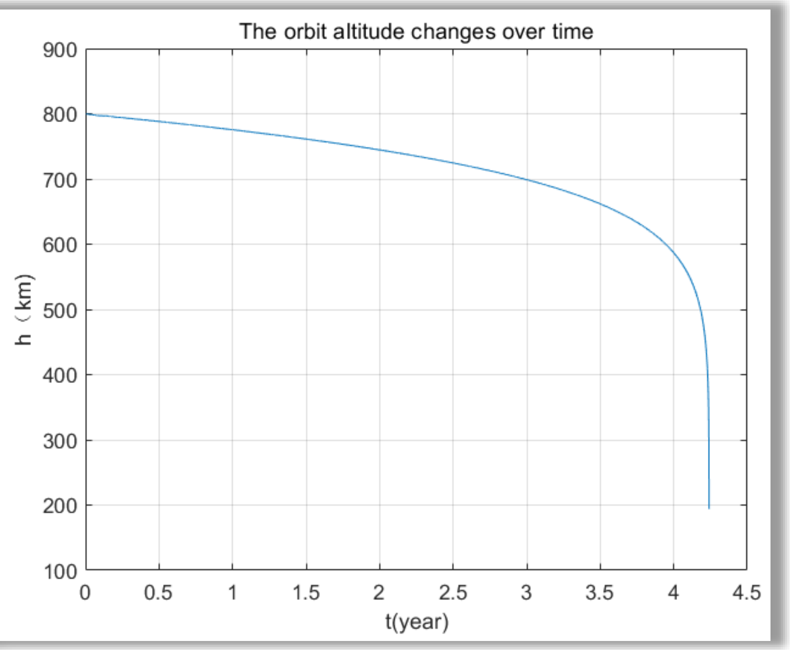


Orbital altitude over time

➢ SINGLE SAIL STRATEGY



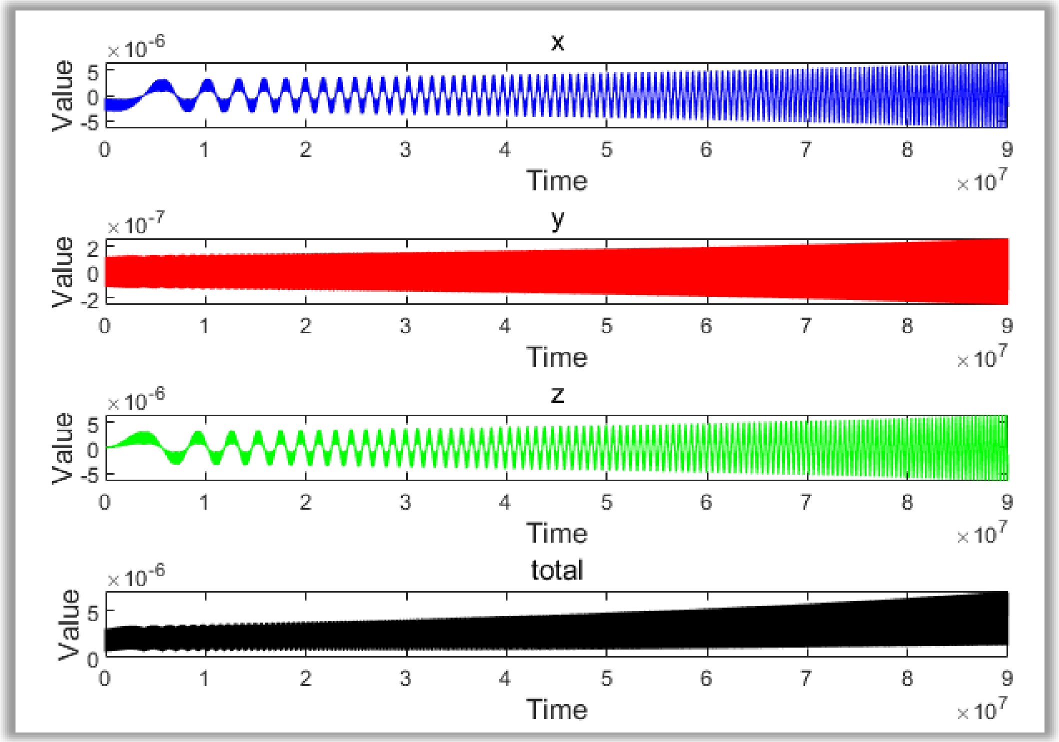
Changes in the six elements of the orbit over time



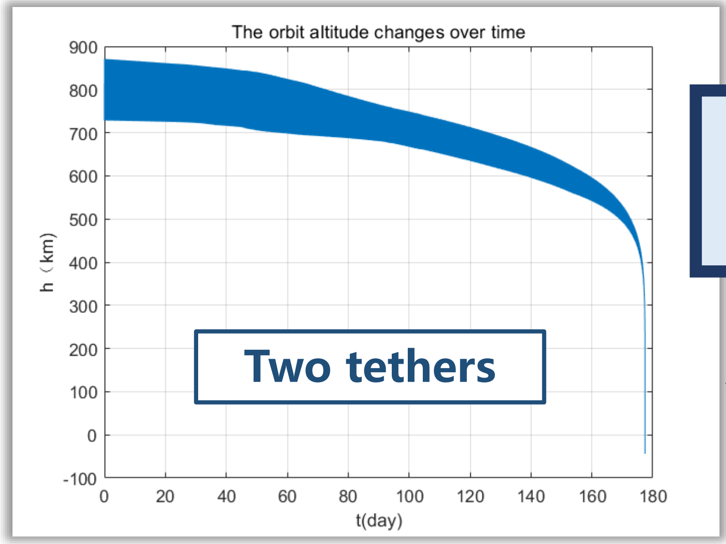
Orbital altitude over time

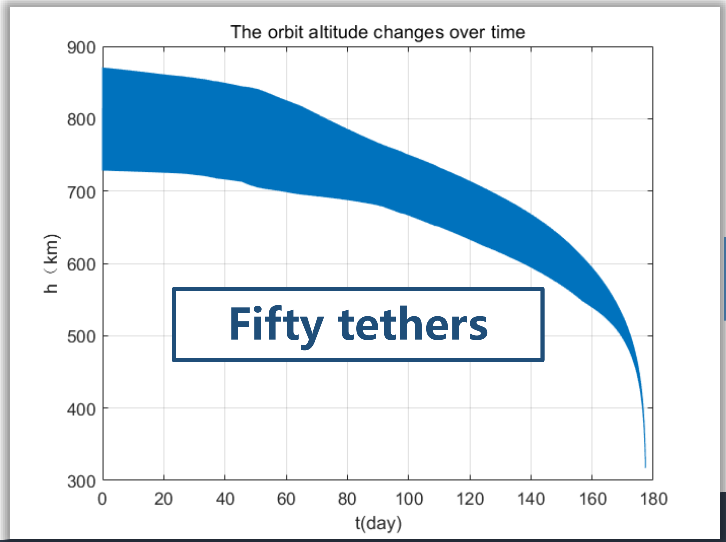
Comparative Analysis of Different Deorbit Strategies

➢ BRAKING SAIL WITH MULTIPLE ELECTRODYNAMIC TETHER ATTACHED



Atmospheric drag over time





Higher de-orbiting efficiency

More tethers More unstable

Comparative Analysis of Different Deorbit Strategies

COMPARISON OF THE EFFICIENCY OF THE THREE STRATEGIES

The targeted altitude for deorbit is assumed to be 250 km

Orbital Height \ time-consuming deorbiting \ Strategies used	SINGLE-TETHER	SINGLE SAIL	HYBRIDSAIL (Braking Sail with Multiple Electrodynamic Tether Attached)
600KM	14.2year	0.28year	0.19year
700KM	18.5year	1.25year	0.8year
800KM	overstep the required level	4.3year	2.72year

SIMULATION RESULTS :

- On low orbits, brake sails have a better de-orbiting efficiency than EDT
- In the combined case, the hybrid strategy is more de-orbiting efficient than either of the other two

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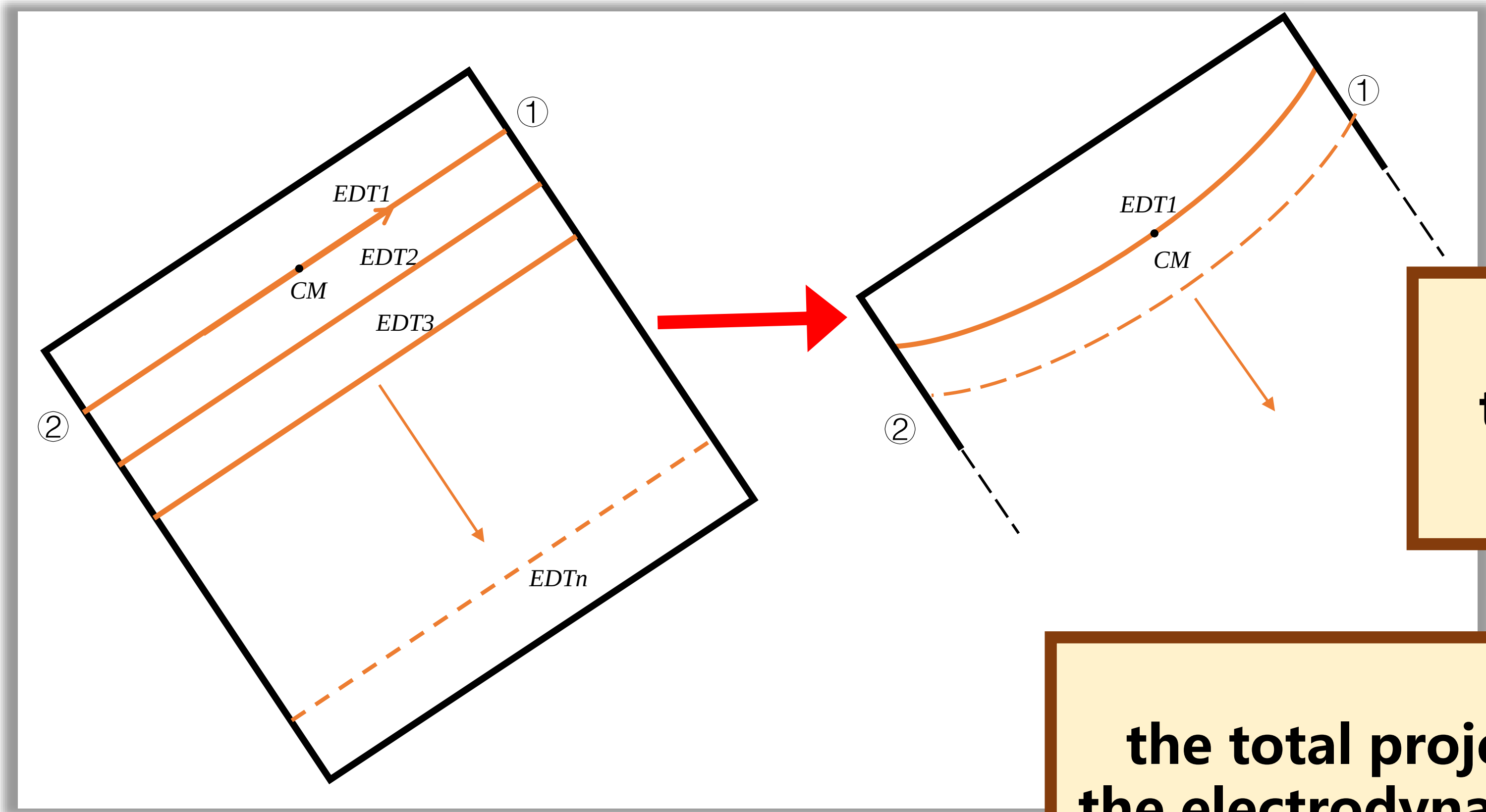
Prospect: Future Work

DEFORMATION OF THE TETHERS



Deformation of
the multiple electrodynamic tethers

SIZE EFFECT

When the spacing is small, there will be interference between the tether segments？

the total projection length remains unchanged the electrodynamic force does not change much？

Prospect: Future Work

POSTURE TRACKING

Maximizing Lorentzian magnetism

Electrodynamic tethers oriented to the ground

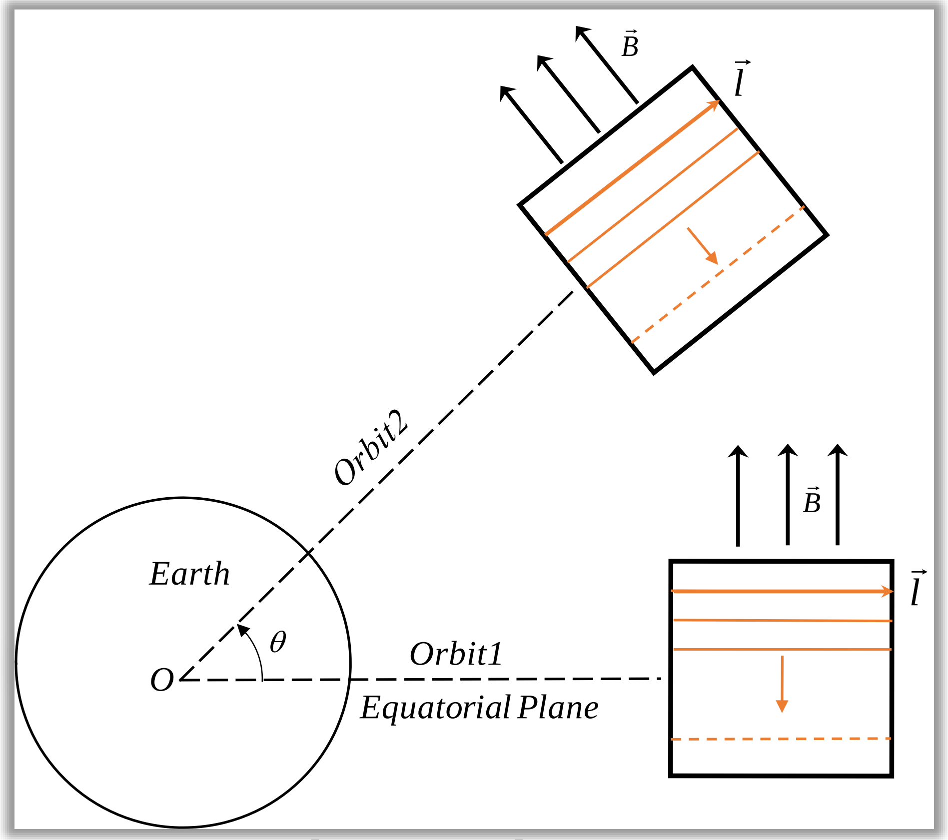
Maximize effective area in the direction of velocity

Rotation control of the satellite body at its interface with the braking sail

Satellite attitude control

one degree of freedom

three degrees of freedom



Ideal conditions
at different orbital inclinations

Prospect: Future Work

CONCLUSIONS AND OUTLOOK

- **Braking sail and electrodynamic tethers combination off-orbit strategy proved to be effective and superior**
- **Establishment of an environment that takes into account space environmental perturbations**
- **New ideas for future spacecraft de-orbiting**