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Graphene Foam Deorbit Sail with Failsafe Release Mechanism

by

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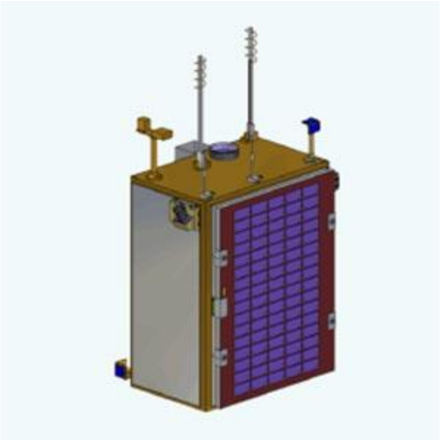
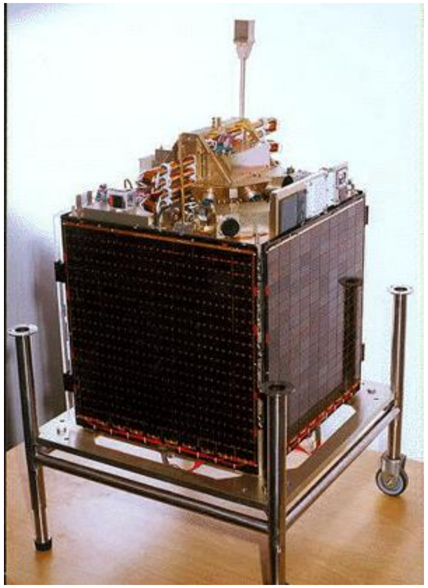
Stellenbosch, South Africa





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Outline

- Background of Deorbit Devices
- Previous Work
- Overview of Sail Design
- Aerodynamic Analysis
- Simulation Results
- Detailed Design
- System Overview
- Questions/Discussion

Overview

Problem Background

Project Description

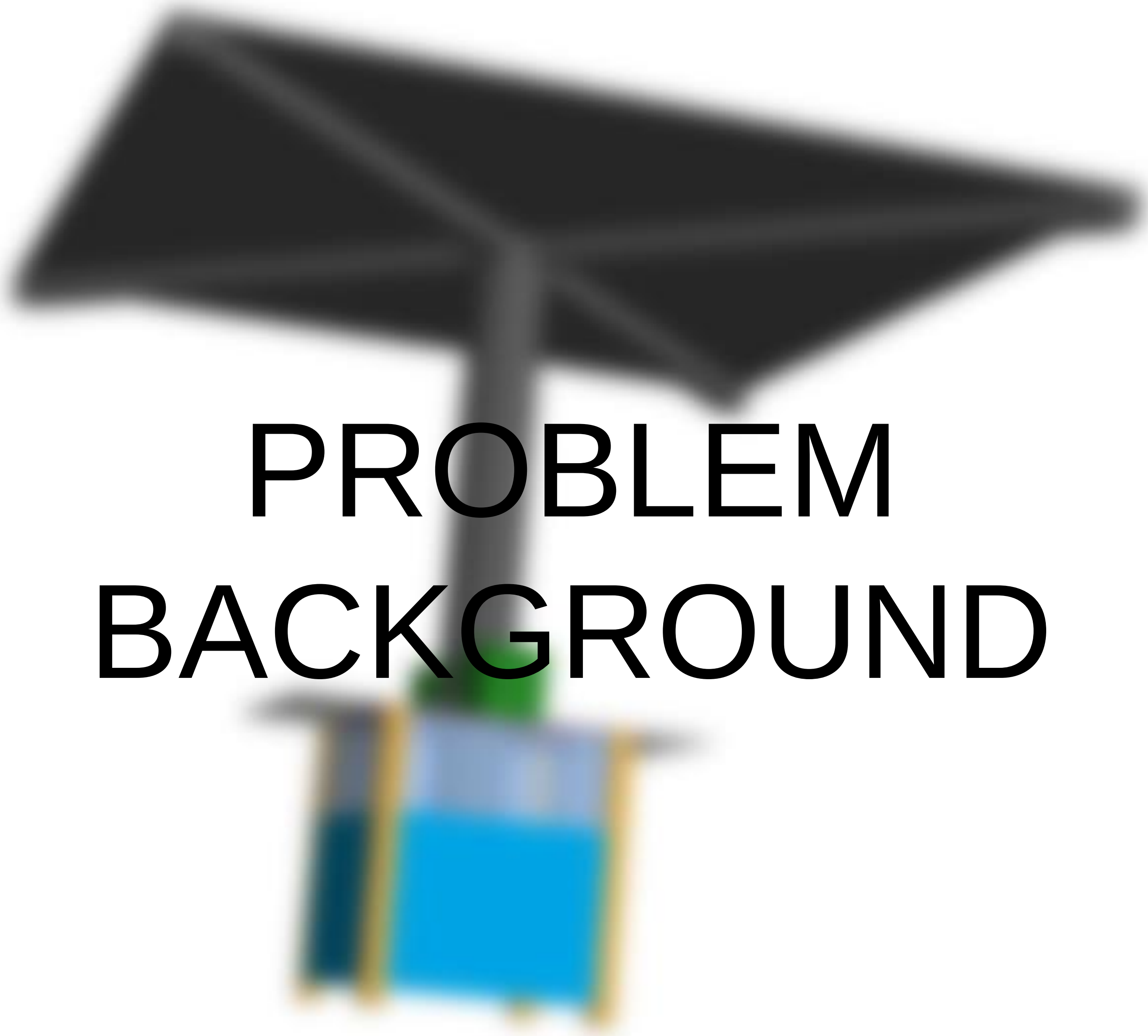
Detail Design

Risk Analysis

Future Work

Questions

PROBLEM BACKGROUND



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Problem Background

- Satellites generally not designed with deorbit time considered.
- Kessler Effect
- Solutions:
  - Active Debris Removal.
  - Deorbit device
- Utilize external forces → avoid use of on-board propellants.
- CubeSats affordable for universities & small companies.

Image courtesy of ESA

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Available External Forces

- Solar Radiation Pressure
  - Highly dependent on satellite orbit.
  - Active attitude control needed.
- Electromagnetic Forces
  - Highly dependent on satellite orbit.
  - Active attitude control needed.
- Aerodynamic Forces
  - Dependent on orbit altitude.
  - Passive attitude control achievable.

Previous Satellite Sail Examples

- Aerodynamic Sails:
  - DeorbitSail
- Solar Sails:
  - Znamya-2.5
  - IKAROS
  - NanoSail-D2 [1]

Image courtesy of SSTL

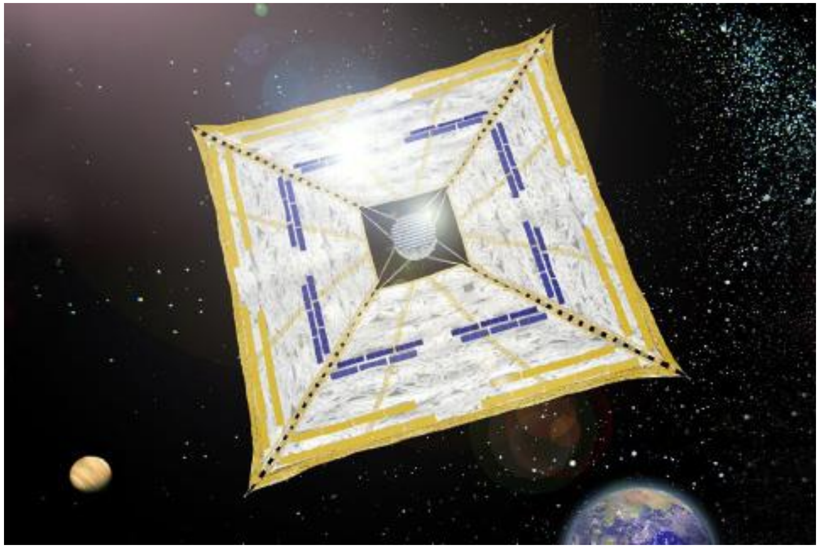


Image courtesy JAXA

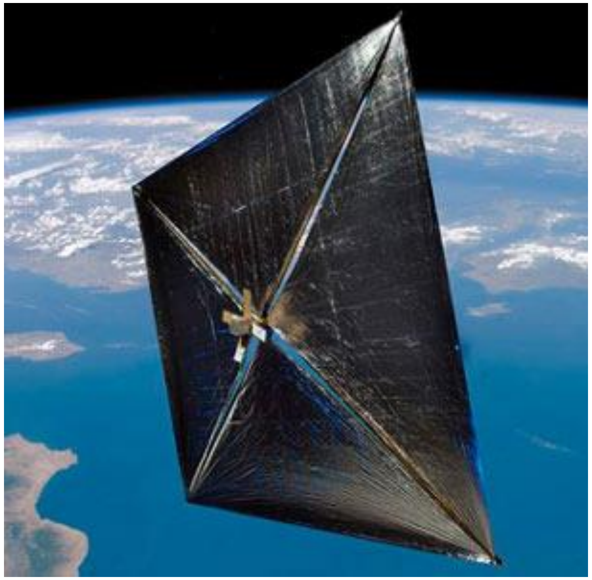
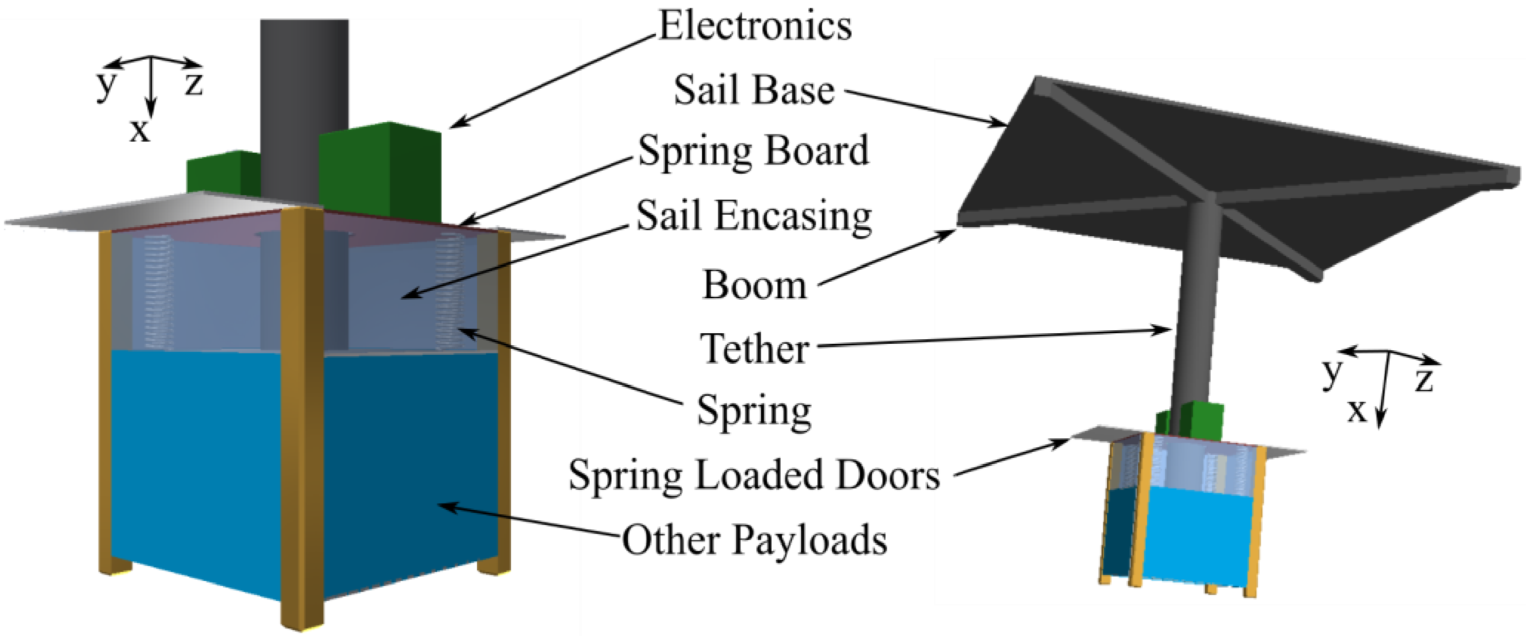


Image courtesy Gunter’s Space Page

Overview of Design

Design Objectives: Significantly reduce deorbit lifetime with reliable, self-deploying sail.



- Passive deployment
- Drag sail consisting entirely of Graphene Foam.
- Independent electronic release system.
- Secondary release system using degradable polymers.

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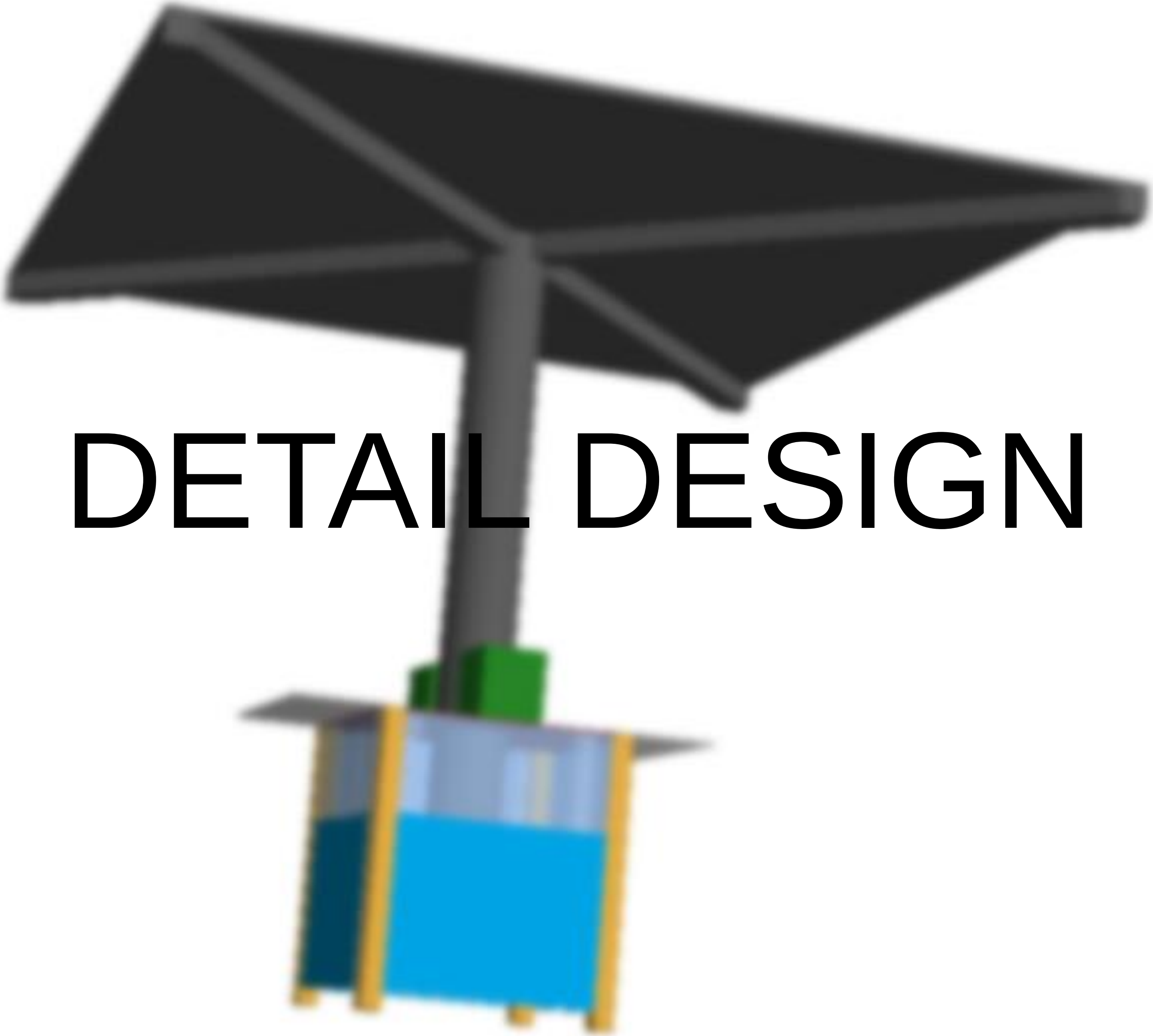
DETAIL DESIGN



Material Selection

Desired properties

- Elastic (self-deployment and compressible), low mass (<0.02g/m^3)

Graphene foam is:

- Thermally stable (-196°C to 900°C)
- Lightweight (0.014 g/cm^3)
- Strong (ultimate tensile strength 5 kPa)
- Elastic (compression of 98% in air, resilient elasticity, Isotropic in compression [2])
- Flexible (0.8 mm bend radius [3])
- Affordable for serious R&D (USD $80.73/cm3, likely to decrease: similar trend expected as in[4])
- Limited possible interference with subsystems (Grounding, Outgassing)

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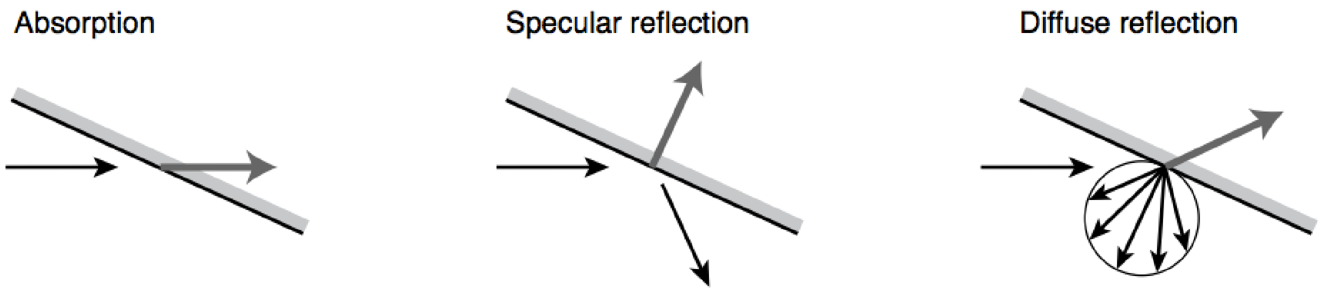
Aerodynamic Analysis

$$F_A = \frac{1}{2}\rho V_\infty^2 S C_d$$

- Estimating drag coefficient:
  - Altitude above 200km → assume free molecular flow [5].
  - Momentum exchange → Industry Standard Sentman Model.



Types of Momentum Exchange [6]

  - Use accommodation coefficient (σ_a) of graphite.
    - Worst case (N_2): $\sigma_a = 0.4 \rightarrow C_d \approx 3$.
    - Expected case: $\sigma_a \approx 0.9 \rightarrow C_d \approx 3.8$.

- Passive stabilisation proven [7][8].
  - CoP behind CoM

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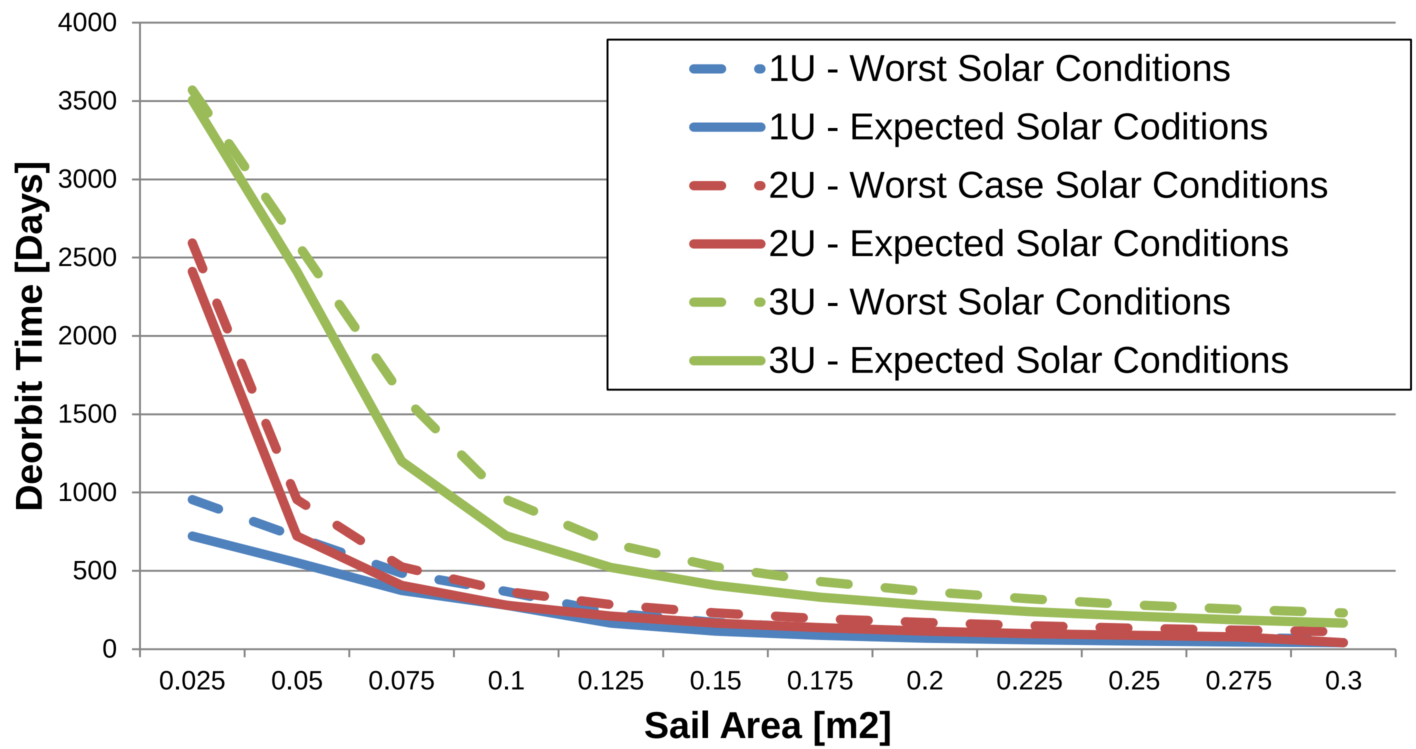
Deorbit Simulations

Deorbit Time vs. Sail Area



Selected Sail Sizes

	1U	2U	3U
Selected Sail Size [m²]	0.04	0.075	0.12
Expected Deorbit Time from 550km [days]	484	526	715
Expected Deorbit Time Decrease	78%	84%	87%

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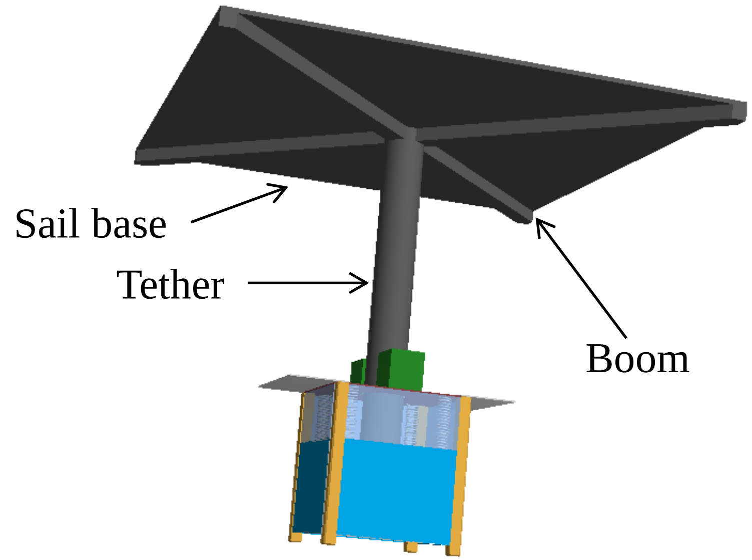
Sail Structure



Design point: >300km altitude

Maximum expected loading:

- 82μN at 300km (1U)
- 246μN at 300km (3U)

Tether:

- >300km altitude (2 - 2.5cm diameter)
- Length dependant on spring loaded doors and width of sail.

Boom:

- Bear aerodynamic load
- Aid deployment
- Modelled as cantilever beams (4mm×2mm and 4mm×2mm)
  - Designed to deflect maximum of 5°, ensures successful drag surface.

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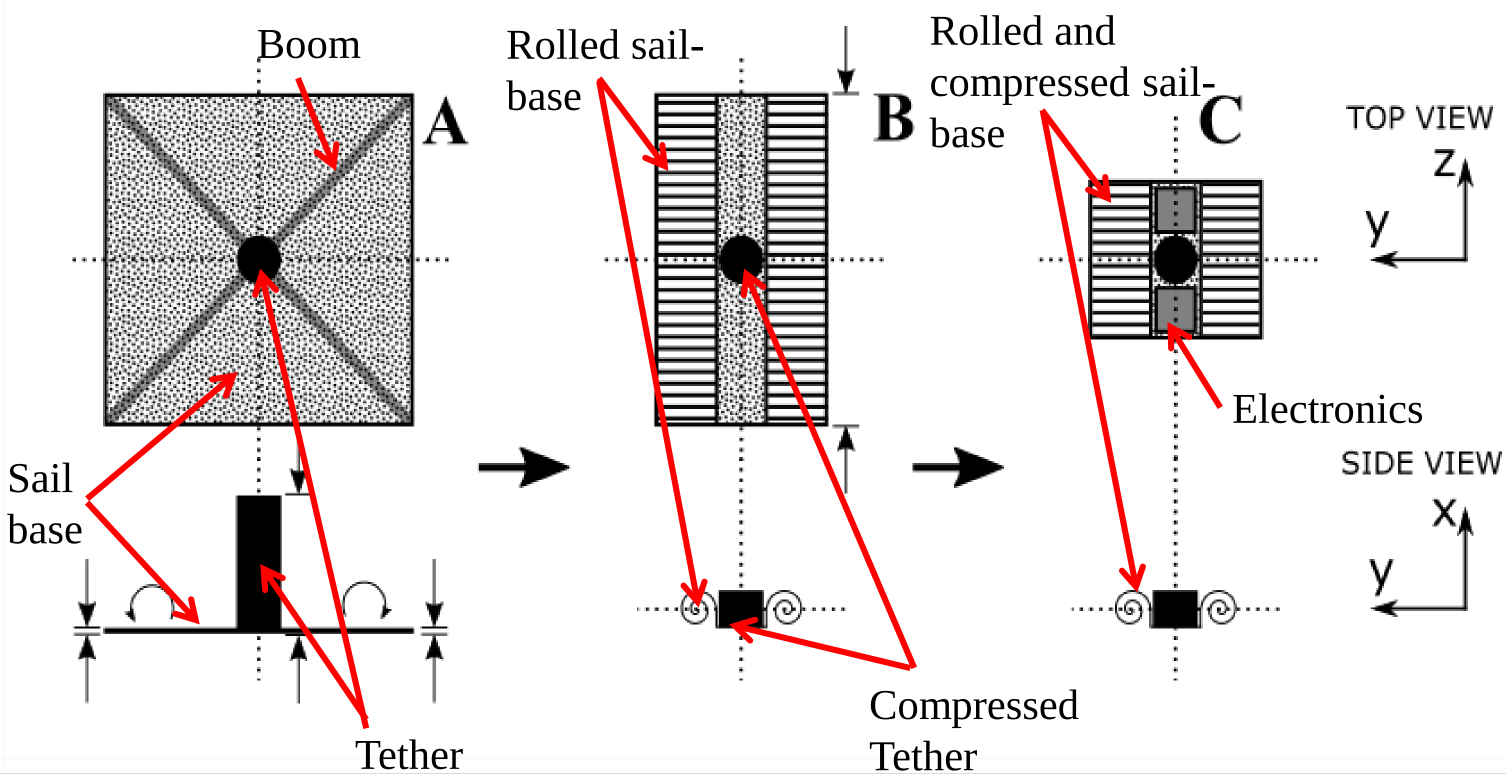
Sail Folding Overview

Design Constraints:

- Bend radius (minimum radius > 0.8mm)
- Compression in Z and X – axes (max compression < 98%)
- Electronics (2[b]cm×3[h]cm×3.65[w]cm)
- Volume of payload (fit within CubeSat)



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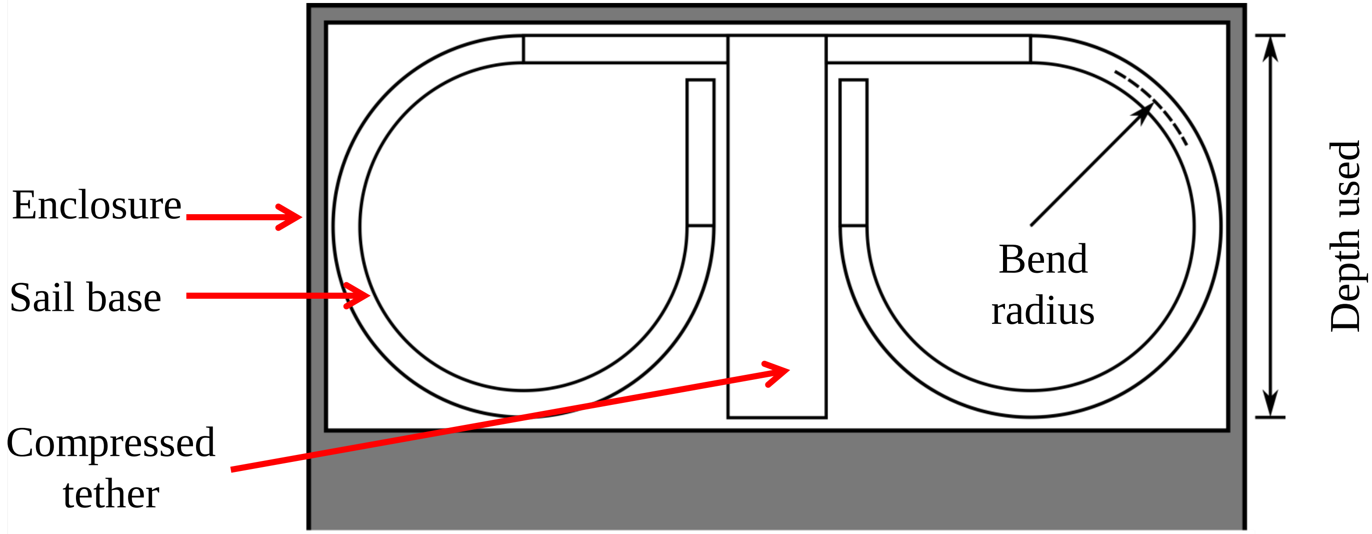
Sail Folding Method 1 (1U)

Purpose:

- Aid passive deployment → folding routine and compressed tether.
- Efficient use of space.
- Conserve structural integrity of sail structure.

Characteristics:

- Maximises bend radius: 13.45mm
- Compression in Z-axis: 52%, X-axis: 81.9%
- Depth of folded sail: 31.9mm results in 0.04m^2 surface area
  - 7mm overhead (doors and springboard)



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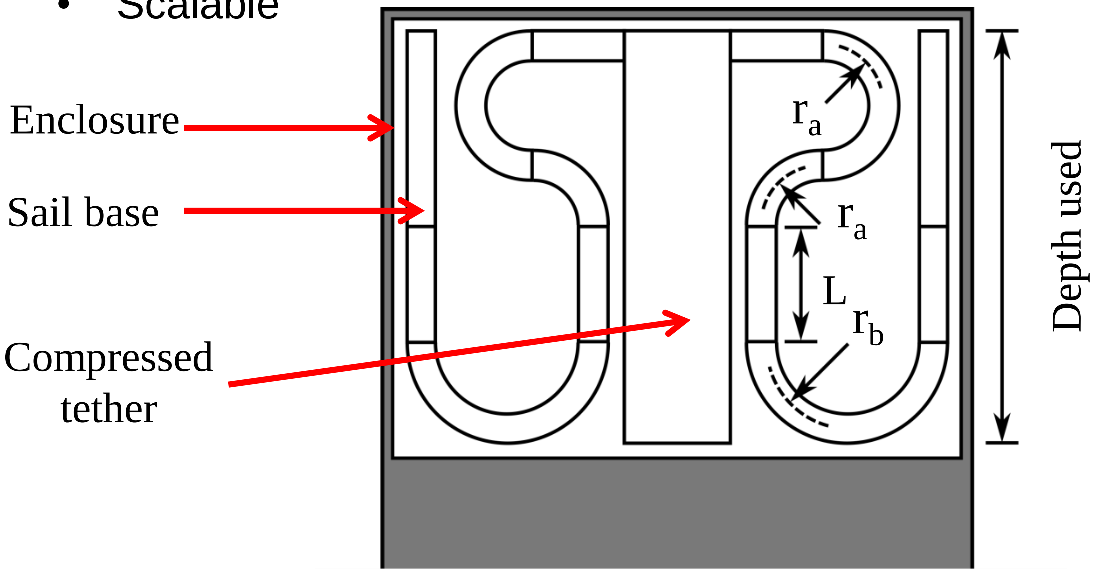
Sail Folding Method 2 (2U+)

Purpose:

- Aid passive deployment → folding routine and compressed tether
- Efficient use of space
- Conserve structural integrity of sail structure

Characteristics:

- Minimum bend radius: r_a, r_b < 12.75mm
- Compression in Z-axis: 72.3%, X-axis: 77.9% (3U) acceptable range
- Depth of folded sail: 61mm, results in size between 0.075-0.12m^2
- Scalable



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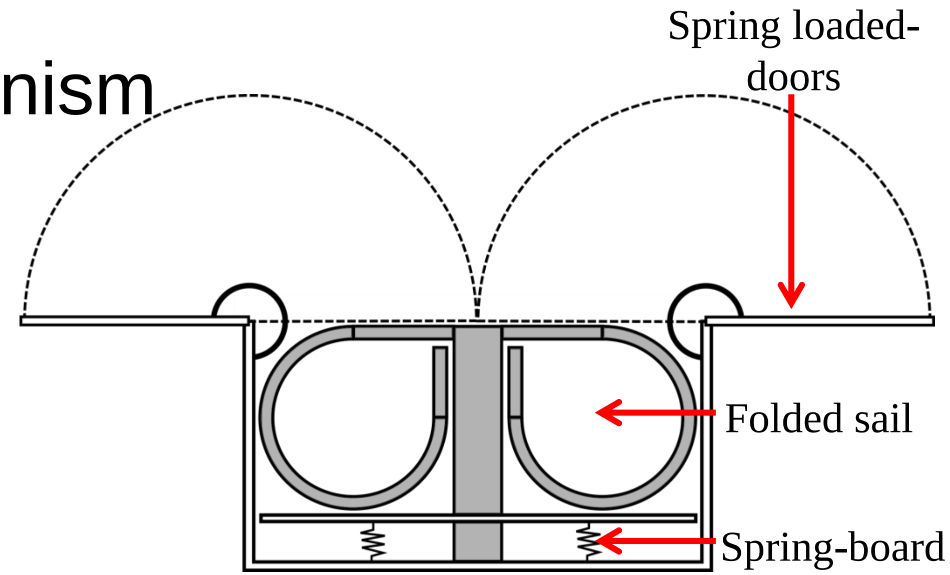
Release Mechanism

Purpose:

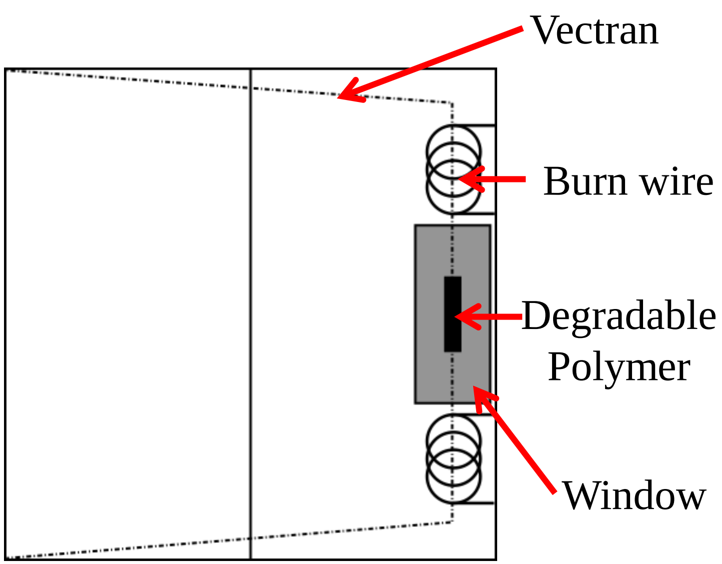
- Aid self-deployment
- Increase redundancy

Features:

- Spring loaded doors
  - Aid passive deployment
- Dual burn wires release spring door
  - Controllable release
  - Dual redundancy
- Exposed polymer degrades due to atomic oxygen, mission specific [9]
  - Added redundancy
  - Sail will deploy after set time period.
- Spring loaded platform
  - Aid passive deployment



Side view



Top view

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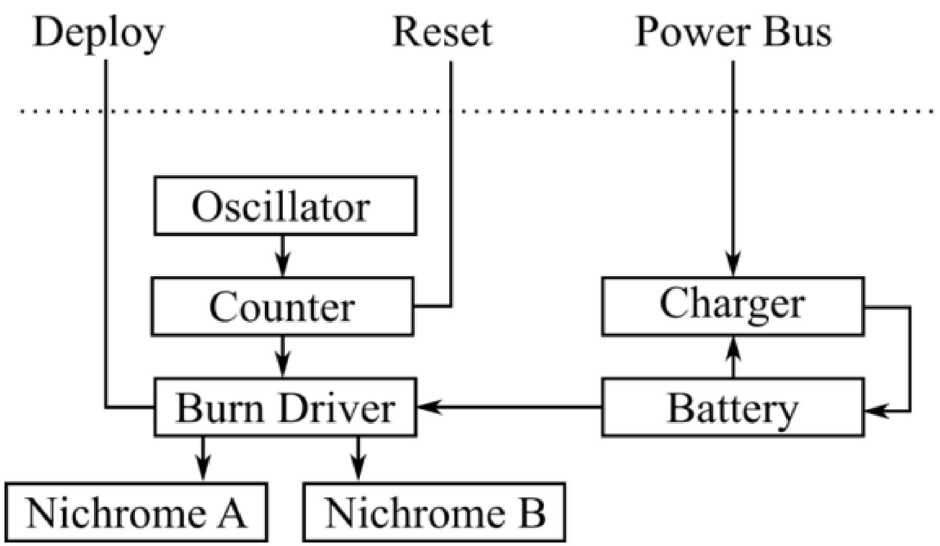
Design: Release Mechanism Circuitry

Purpose:

- Actuate burn-wires after certain period of time.

Characteristics :

- Independent electronics: operation possible despite power bus failure for > 3 months.
- Receives commands via satellite bus.
- Charged by satellite bus during normal operation ($P_{charge} \approx 20mW$).



Risk Analysis

Damage to Deorbit System ↑

• Space environment affects structural integrity of graphene foam. • Folding method damages sail.	• **Deployment failure** • Premature deployment.	
• Sail not structurally strong enough to withstand drag forces.	• Generating additional debris. • Burn wire failure. • Complete power loss.	
Satellite power failure.		

Probability of Occurrence →

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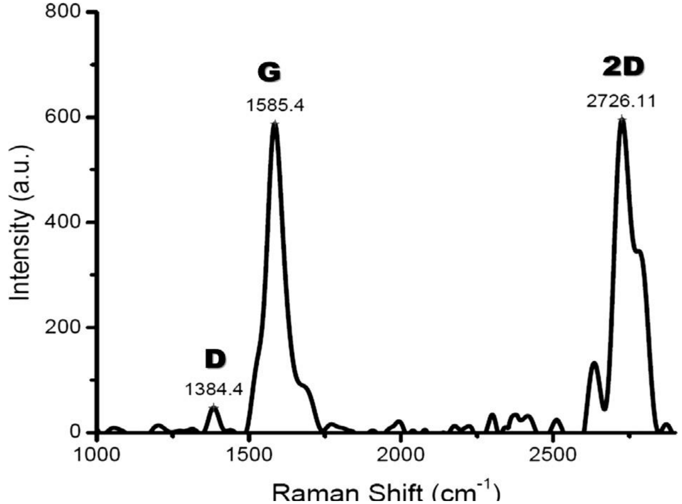
Development Strategy

Graphene Foam Testing

- Deployment testing
- Environmental Testing (radiation and thermal-vacuum)
- Verify structural integrity using Raman Spectrum (D/G ratio indicates amount of defects).
- Determine outgassing effects.
- Determine precise relationship between minimal allowable bend radius and thickness of foam → more efficient packing scheme possible.
- Determine accommodation coefficient .

Degradable Polymers

- Test potential outgassing effects.
- Verify structural lifetime.



Raman Spectroscopy of Graphene foam [10].

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Conclusion

Graphene foam's desirable properties along with the simple and innovative packaging method warrant:

- **Reliable deployment**
  - Independent electronic system
  - Self-deploying structure (no moving parts)
  - Failsafe release (backup degradable polymer)
- **Passive stabilisation**
- **Reduction** of deorbit time by at least **75%**
- **Scalable** to larger than 3U utilising Folding Method 2.

Deorbit device objectives reached.

Only the beginning…

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Thank You!
QUESTIONS?

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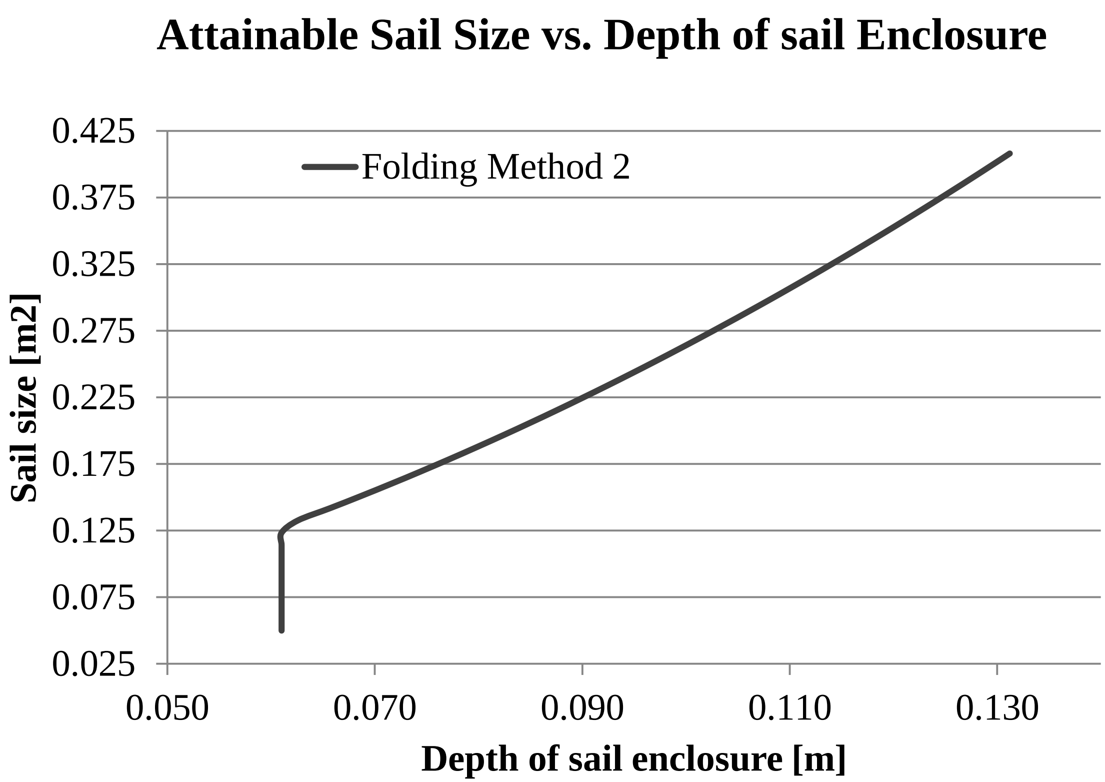
Extra Slides: Scalability of Method 2



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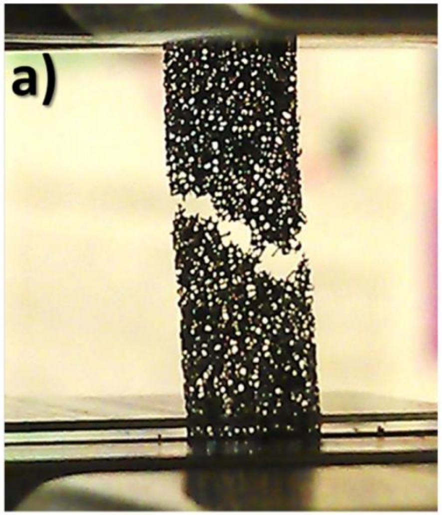
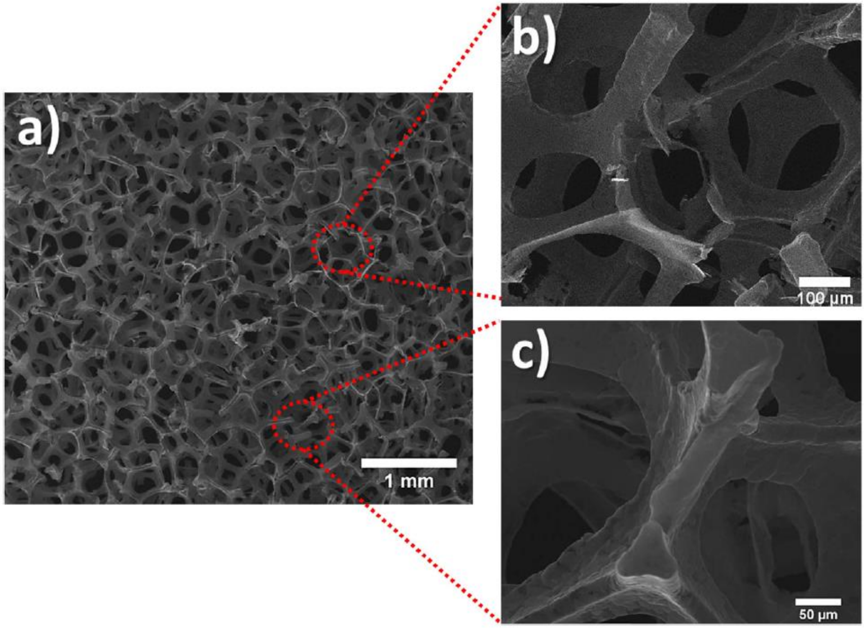
Extra Slides: Details of 1U, 2U, 3U

Attribute	1U	2U	Scale	3U	Scale
Area of deployed square sail [m^2]	0.04	0.075	1U x 1.87	0.12	1U x 3
Mass of deorbit device payload [kg]	0.225	0.26	1U x 1.15	0.265	1U x 1.17
Typical mass of CubeSat[kg]	1.0	2.0	1U x 2	4.0	1U x 4
Envelope encasing dimensions [mm]	98 x 98 x 38.9	98 x 98 x 68	1U x 1.74	98 x 98 x 68	1U x 1.74
Average Power [W]	0.03	0.03	1U x 1.0	0.03	1U x 1.0
Power (release) [W]	3.84	3.84	1U x 1.0	3.84	1U x 1.0
Ballistic coefficient [kg/m^2]	8.33	8.88	1U x 1.07	11.11	1U x 1.33
Expected Deorbit time with sail [days]	484	526	1U x 1.09	715	1U x 1.48
Estimated Cost [USD]	$45,208	$74,998	1U x 1.65	$92,302	1U x 2.04
Maximum orbit altitude [km]	750	750	1U x 1	700	1U x 0.93

Extra Slides: Structure



Graphene undergoing UTS test with initial dimensions: 16mmx5mmx0.2mm [10].



High magnification of 3D graphene foam network [10].

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Extra Slides: Atomic oxygen

Combination of UV and atomic oxygen aggregates degradation rate.

The biggest concentration of atomic oxygen is present above 100km altitude.

Atomic oxygen is formed by solar UV radiation dissociating oxygen molecules into free oxygen atom. This occurs mostly above 100km altitude.

Atomic oxygen is highly corrosive, combining with most materials they encounter. [11].

Extra Slides: Air Density Model