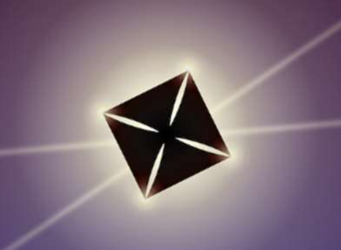
Piotr Fil
Gil Barbosa Ribeiro
Debdut Sengupta
Beatriz Soriano Tortosa

PROJECT **SVAROG**



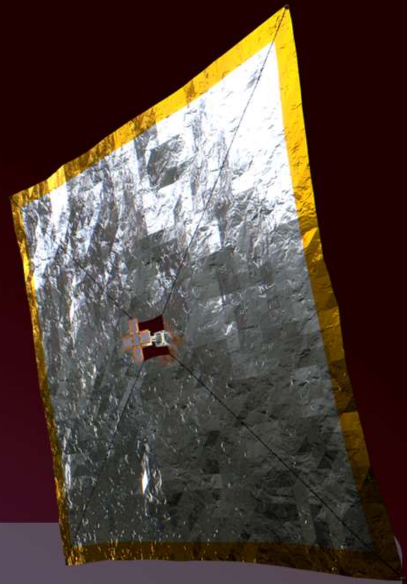
Research for an Early-Stage Development of the First Interstellar CubeSat Powered by Solar Sailing Technology

5th June 2023

Imperial College London

The Goal

Our mission is to **push forward solar sailing** technology and demonstrate **low cost interstellar travel** accessible to student projects.



This is a multi-year project which aims to send an interstellar solar sailing spacecraft. The project's primary objective is to:

Construct a craft that will reach the heliopause (assumed at 123 AU from the Sun) within 100 years from launch by using solar sail technology.

Additionally, the mission has the following secondary objectives.

1. *Measure the trajectory of the craft and validate it against theoretical models*
2. *Get a visual confirmation of deployment*
3. *Carry a payload representing human ingenuity on board*

The Trajectory

The key element of the mission is to use a sundiver design with passive spin stabilisation:

- The attitude is selected so that at perihelion spacecraft is generating maximum thrust.
- The spin rate is sufficiently high, such that the dynamics of precession are decoupled from spin.
- Possibility of delivering a lightweight payload into orbit with high delta-v requirements.

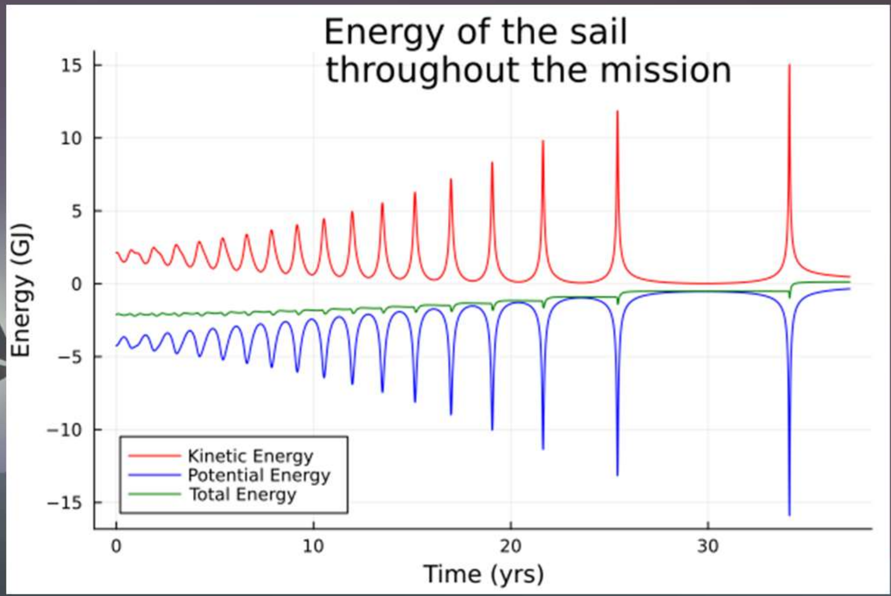
Step 1:

a) Spacecraft is launched on a **smaller-than-Earth velocity** orbit as a secondary payload to maintain low costs.

b) **Booms** with low thrust solid thrusters are deployed to spin-up the sailcraft.

c) Sail is quasi-dynamically deployed by the **inertial forces**.

d) Sail is deployed at aphelion of transfer orbit and starts **deccelerating** with respect to the Sun.



1. Esme H. Moore (2019). Feasibility analysis of a solar sail propelled spacecraft for extrasolar trajectories. Master thesis supervised by Aaron Knoll
2. Filippos V. Geragidis (2020). Preliminary design of a solar sail propelled spacecraft for extrasolar trajectories. Master thesis supervised by Aaron Knoll
3. Pauline Montete (2021). Preliminary Structural design of a solar sail propelled spacecraft for extrasolar trajectories. Master thesis supervised by Aaron Knoll

The Trajectory

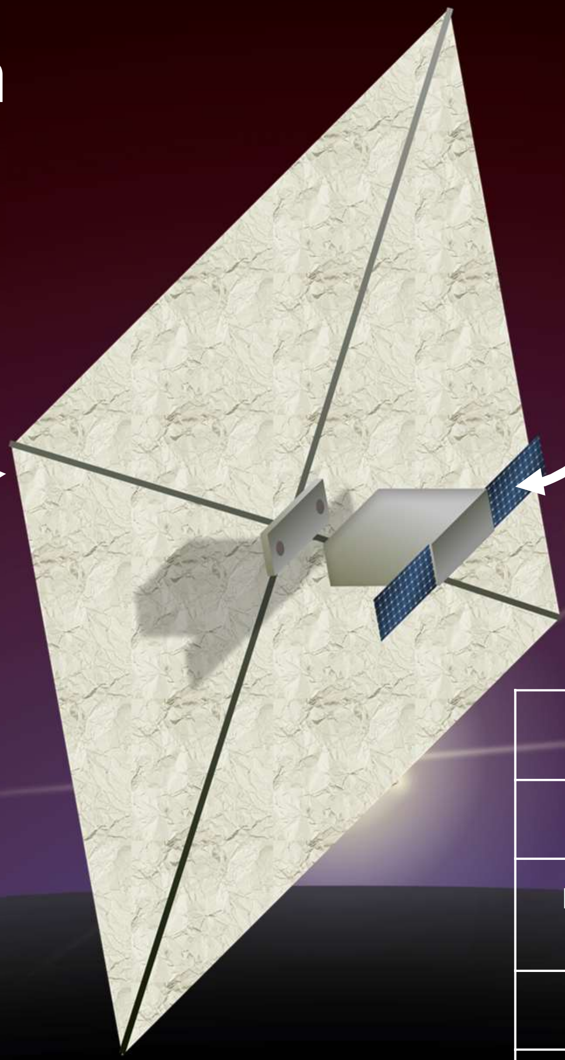
Step 2:

- In a simplified view the sail can be modeled as a **low thrust propulsion system** with a velocity parallel to its orbit. The radial component is negligible with respect to gravity.
- With the fixed attitude, this leads to **step-like total energy behaviour**, which results in achieving an escape velocity.

This trajectory imposes strict mass requirements

The Svarog System

To lower the sailcraft's mass, the Svarog System is made out of two separate components:



Sailcraft

- Passive, ultralight spacecraft that will leave the Solar System
- Fitted with a beacon for one-way tracking

Carrier Probe

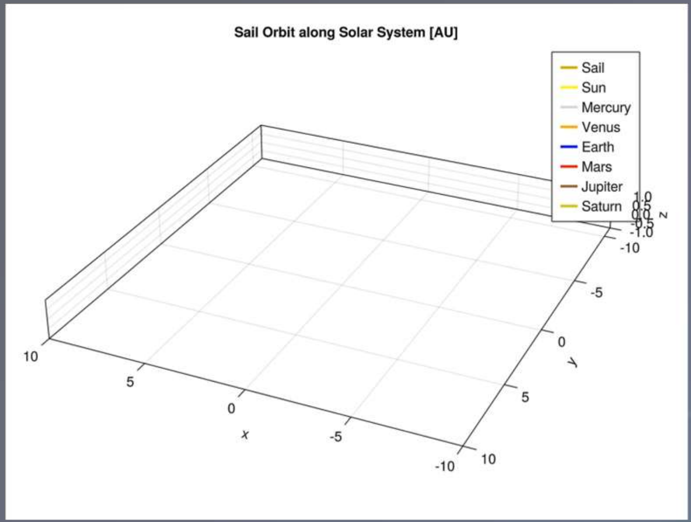
- Protects the sail during launch
- Unfolds, spins up and releases the sail on deployment
- Detaches from the sail to lower its mass

Technical data:

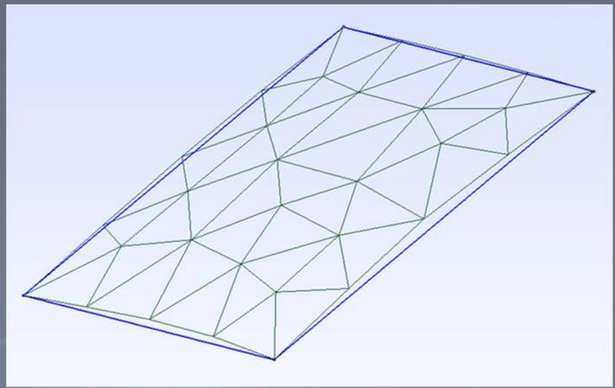
Sailcraft	Carrier Probe
15x15 m sail	6U CubeSat
Mass/Area Ratio of 12 g/sqm	Spun up by solid rocket on booms
Kapton Sail, 5 µm thick	3 Onboard Cameras
Trackable to 10 AU	~5 kg mass

Mission Characterisation Plan

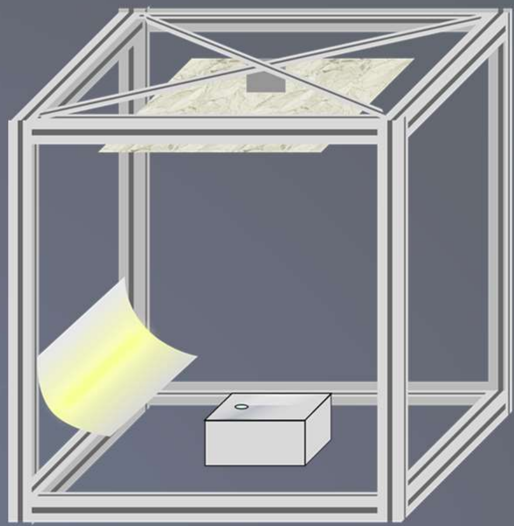
Orbital Trajectory Simulations



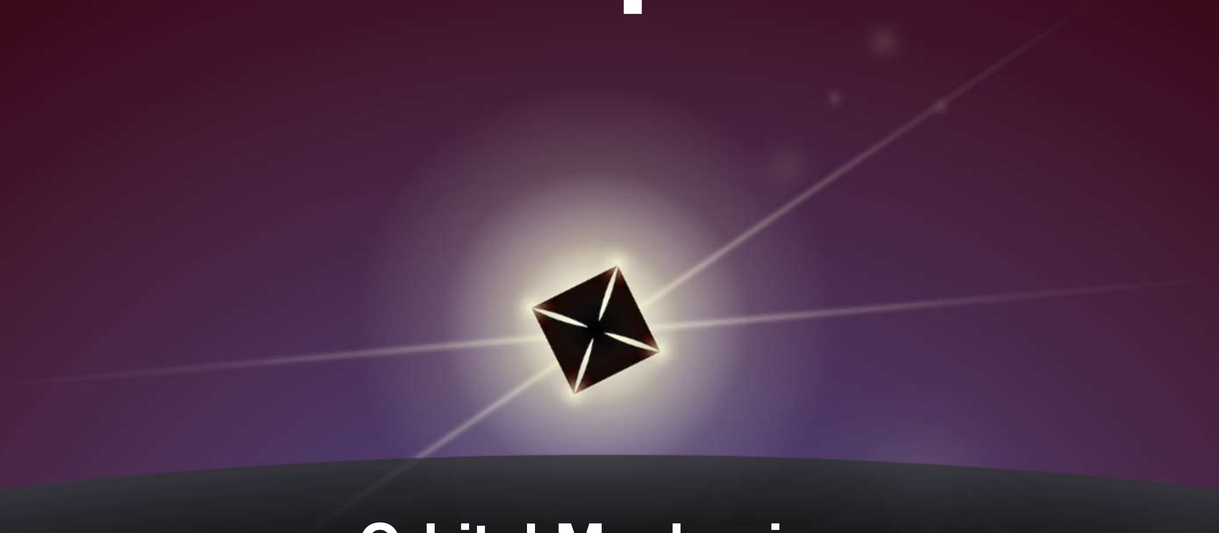
Structural Models of
Sail Deformations and Stability



Experimental Results



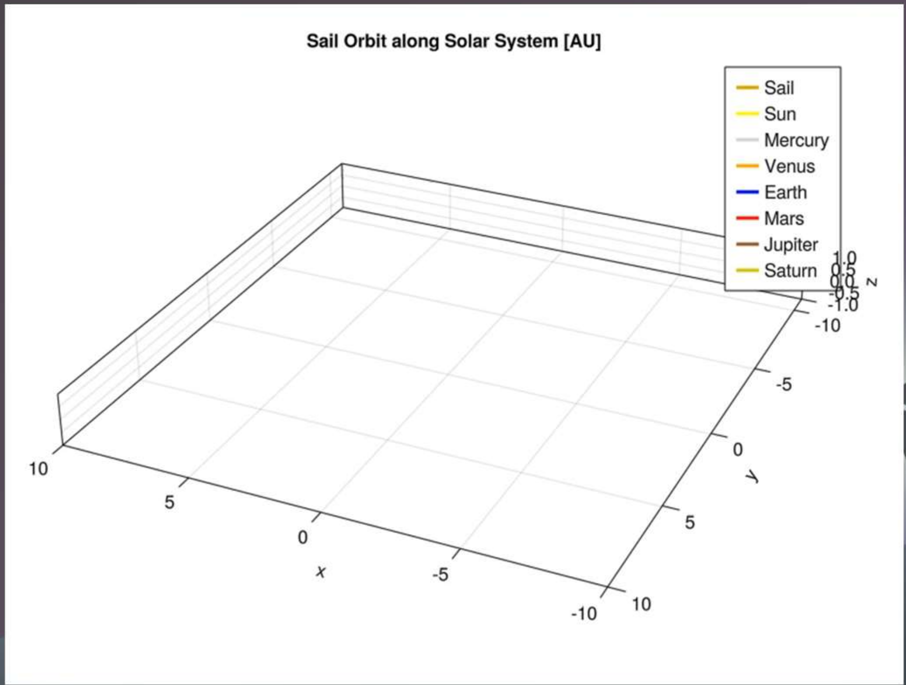
Mission Development

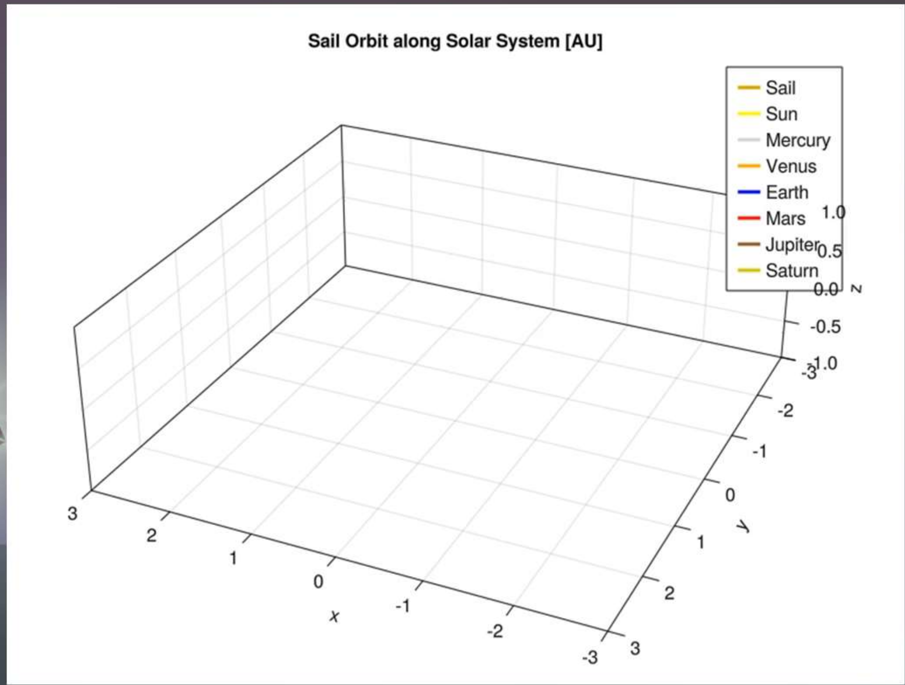


Orbital Mechanics

Orbital Stability

Full 6 DoF motion with n-body correction and relativistic effects.





Mission Development

Structural Mechanics

Structural Mechanics

Equations of Motion

Lagrangian:

$$L = E_k - E_p$$

Euler-Lagrange Equation:

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{x}_i} - \frac{\partial L}{\partial x_i} = F_i$$

Structural Mechanics

Non-dimensionalization

Length Scale

$$x = X\bar{x}$$

Time Scale

$$t = T\bar{t}$$

Euler-Lagrange Equation

$$\frac{d}{T d\bar{t}} \frac{\partial}{\frac{X}{T}\partial \bar{x}'_i} L - \frac{\partial}{X \partial \bar{x}_i} L = F^* \bar{F}_i$$

Structural Mechanics

Solution for Multi-Particle Model

Dimensionalized

$$E_k = \sum_{i=1}^{NODES} \frac{1}{2} m_i \dot{x_i}^2$$

$$E_p = \sum_{i=1}^{EDGES} \frac{1}{2} k_i (|x_{i1} - x_{i2}| - l_i)^2$$

Non-dimensionalized

$$E_k = \frac{MX^2}{T^2} \sum_{i=1}^{NODES} \frac{1}{2} \bar{m}_i \bar{x}_i'^2$$

$$E_p = KX^2 \sum_{i=1}^{EDGES} \frac{1}{2} \bar{k}_i (|\bar{x}_{i1} - \bar{x}_{i2}| - \bar{l}_i)^2$$

Structural Mechanics

Solution for Multi-Particle Model

$$\frac{MX^2}{T^2}\bar{m}_i\bar{x}_i'' + KX^2\sum_{j=1}^{NEIGH}\frac{\bar{x}_j-\bar{x}_i}{|\bar{x}_j-\bar{x}_i|}k_i(|\bar{x}_j-\bar{x}_i|-\bar{l}_i) = XF^*\bar{F}_i$$

$$\left(\frac{MX}{T^2F^*}\right)\bar{m}_i\bar{x}_i'' + \left(\frac{KX}{F^*}\right)\sum_{i=j}^{NEIGH}\frac{\bar{x}_j-\bar{x}_i}{|\bar{x}_j-\bar{x}_i|}k_i(|\bar{x}_j-\bar{x}_i|-\bar{l}_i) = \bar{F}_i$$

Inertial Group:

$$\frac{MX}{T^2F^*}$$

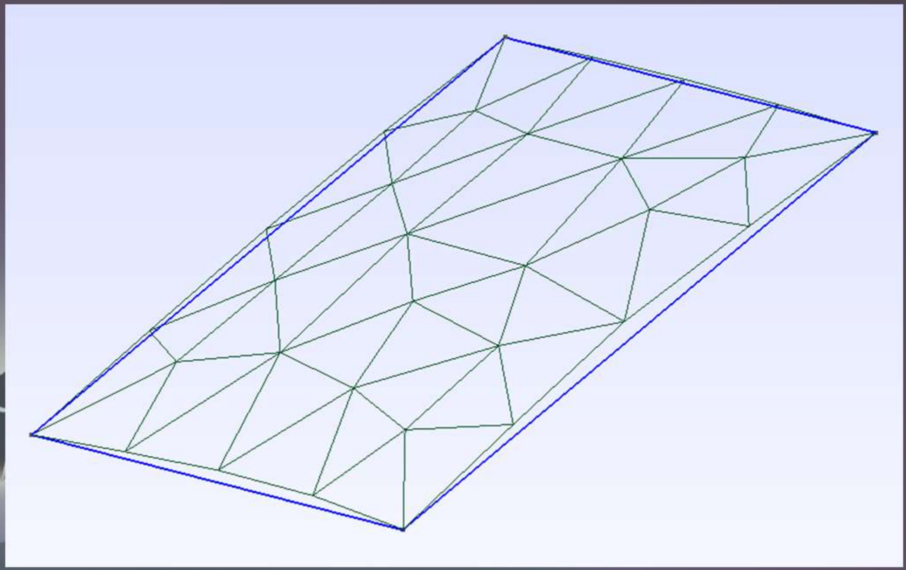
Stiffness Group:

$$\frac{KX}{F^*}$$

Structural Mechanics

Multi-Particle Model

- The nodes represent masses and the edges represent springs.
- This case represents a square membrane constrained at the corner nodes.
- Arbitrary boundary conditions can be applied.

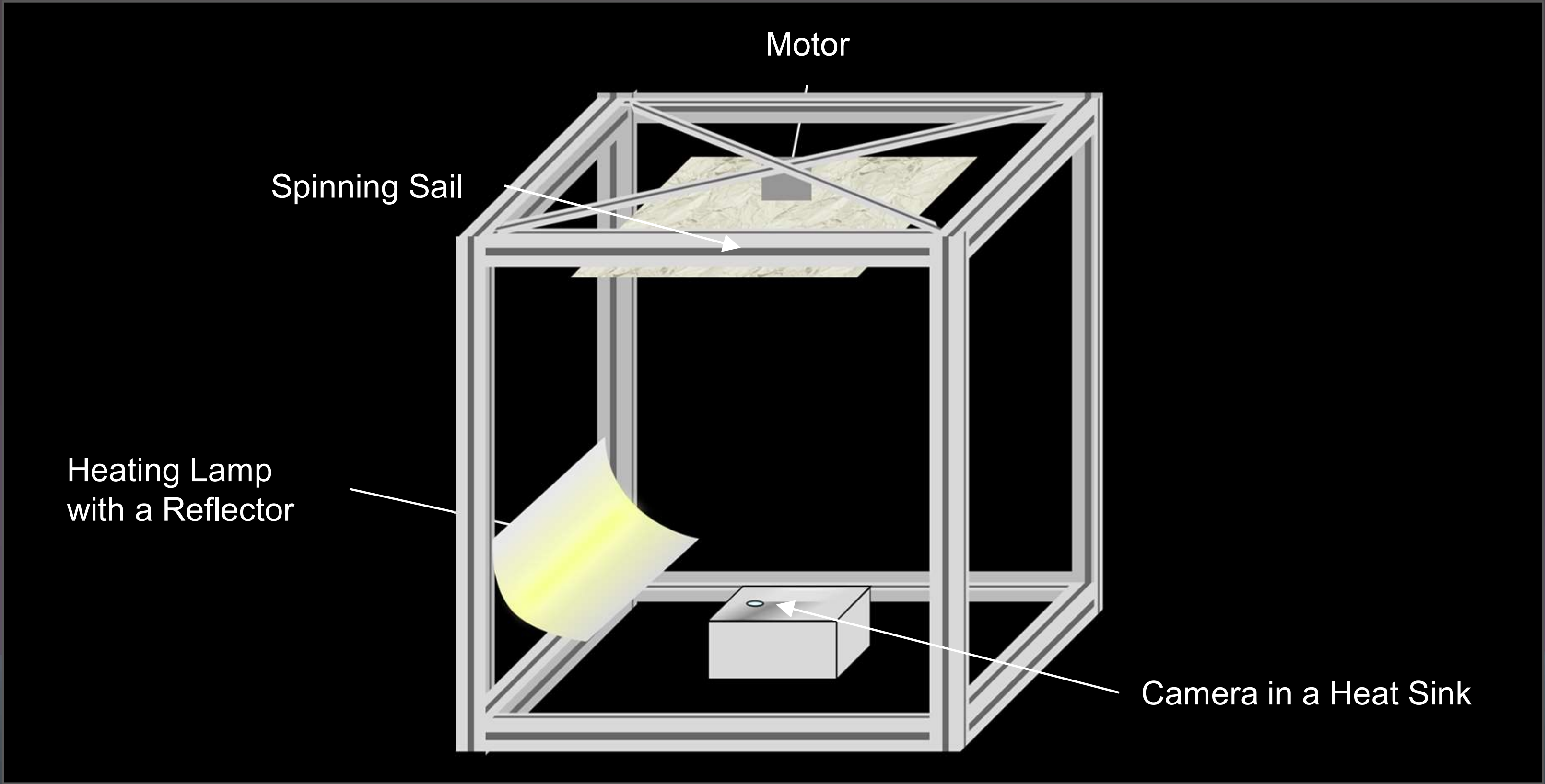


Mission Development

Experimental Work

The Vacuum Chamber Experiment

Schematics



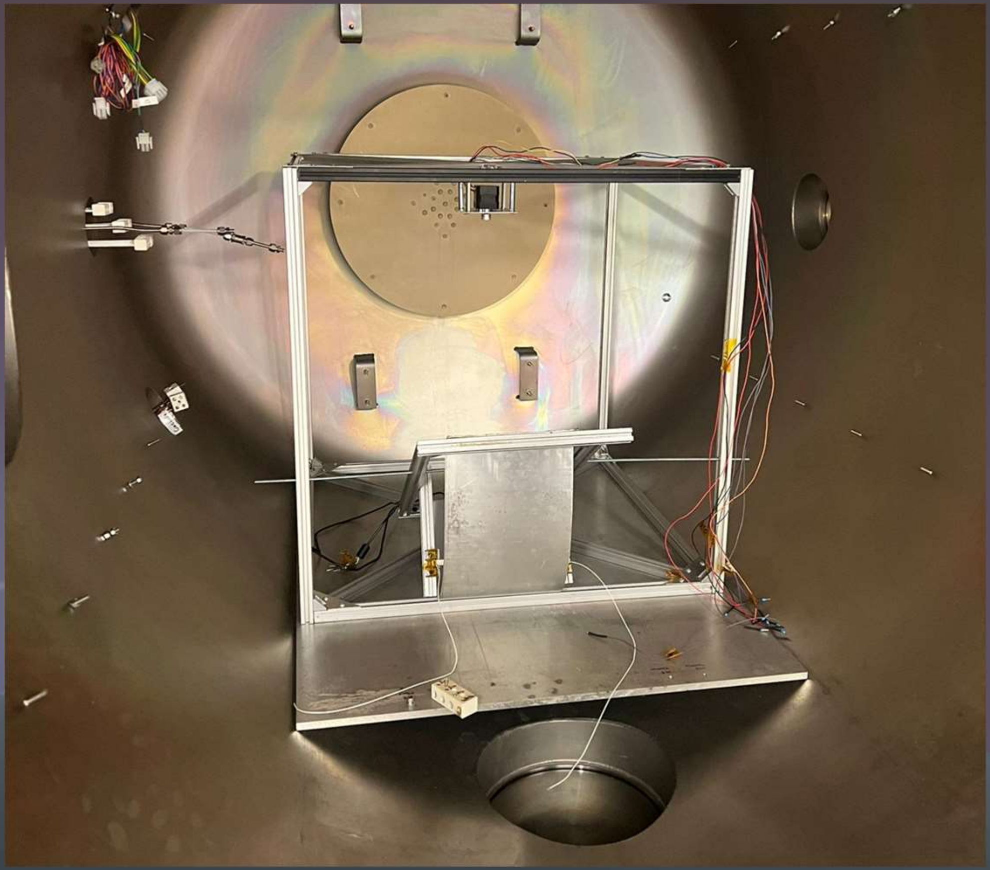
The Vacuum Chamber Experiment

Set-up

- Cables organized as separate connections for the motor, camera, mains and lighting.

- For low frequency signals, custom-made feedthroughs were used.

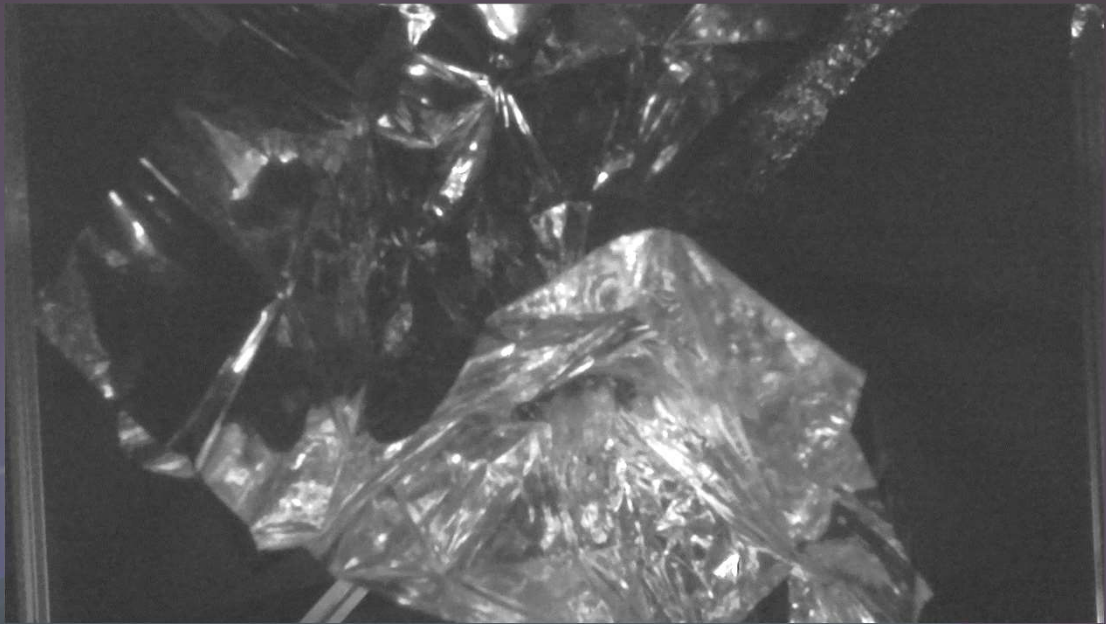
- A high-frequency USB signal was transmitted via custom-made USB to D-SUB converters.



The Vacuum Chamber Experiment

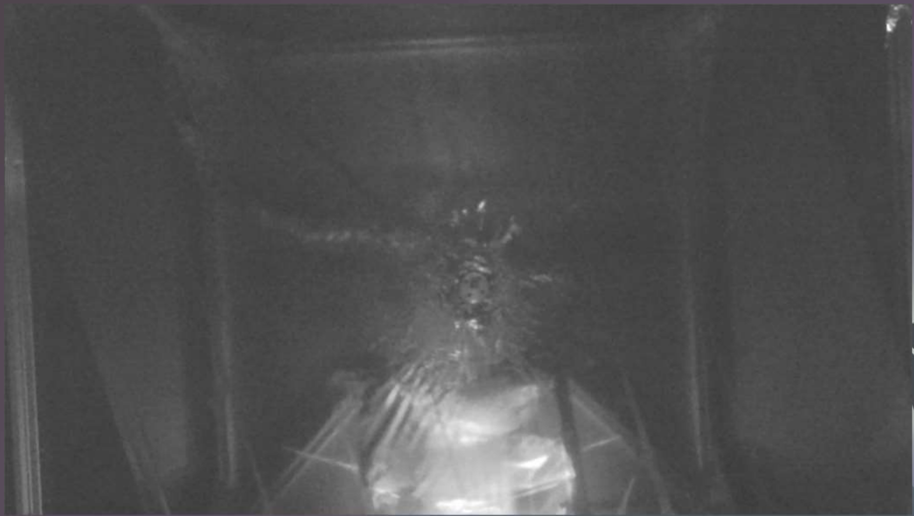
Recorded Video

- Rotation speed varied from 100 RPM to 1000 RPM
- Change of dynamic mode at 650 RPM

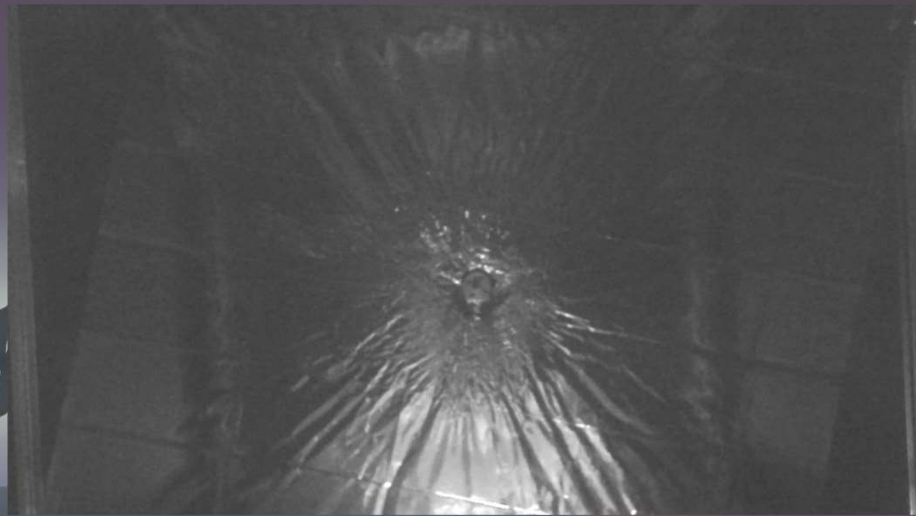


The Vacuum Chamber Experiment

Dynamic Modes - Membrane



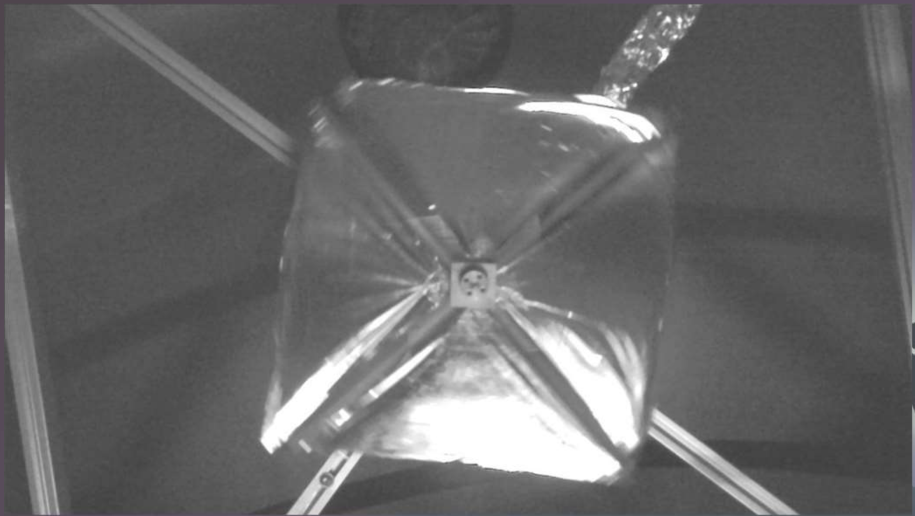
Stiffened membrane



Buckled membrane

The Vacuum Chamber Experiment

Dynamic Modes - Booms

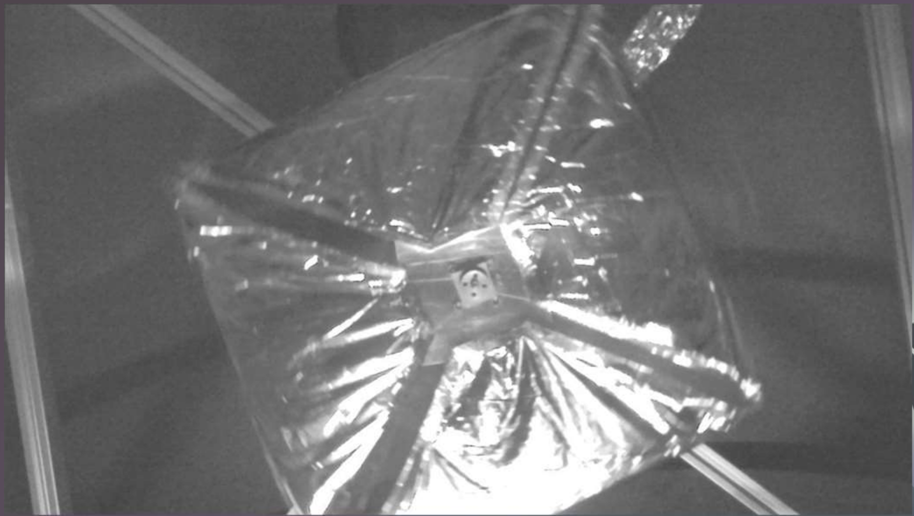


High-speed wrinkling

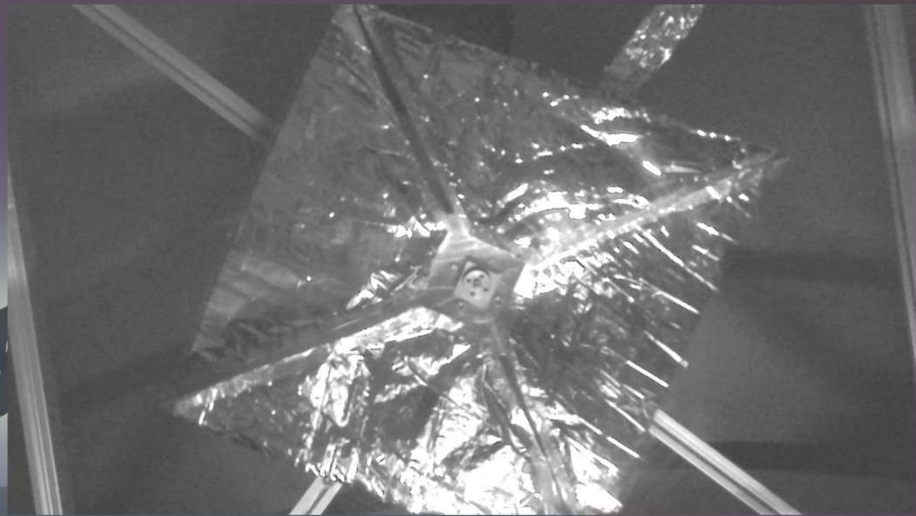
Boom torsional buckling

The Vacuum Chamber Experiment

Dynamic Modes - Cable Tensioned



High-speed tensioned

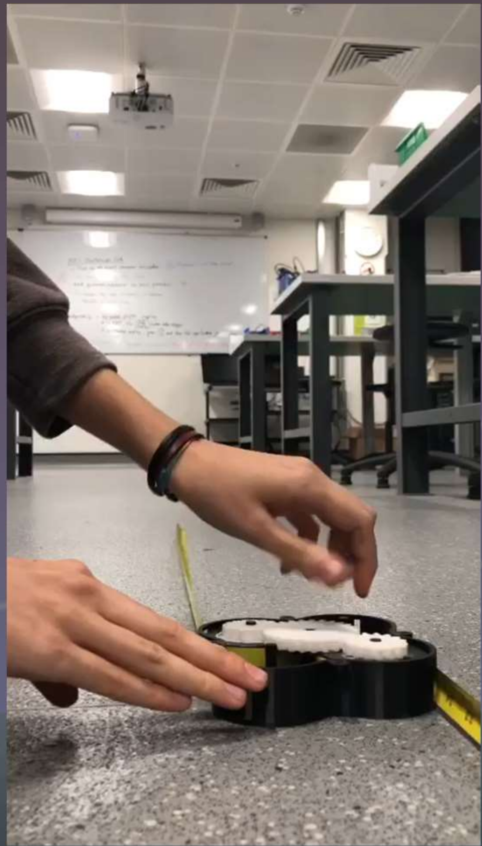


Global buckling

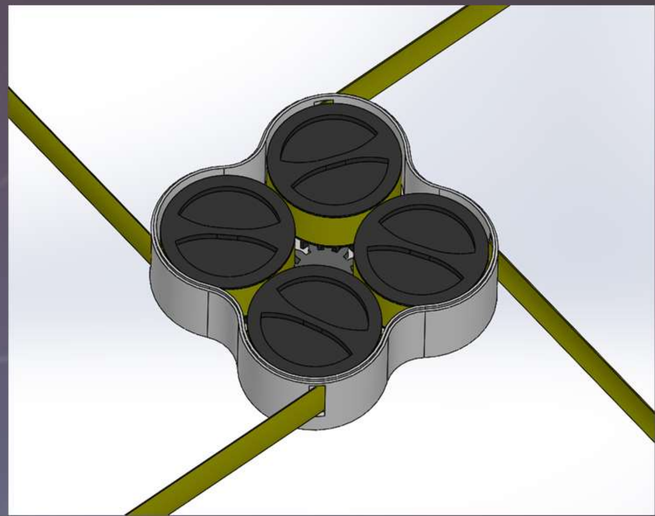
Mechanical Prototyping

Boom Deployment

- Gain a practical understanding of the sail's deployment process.
- Investigate self-deployable methods.
- Explore buckling and 'blooming' issues.

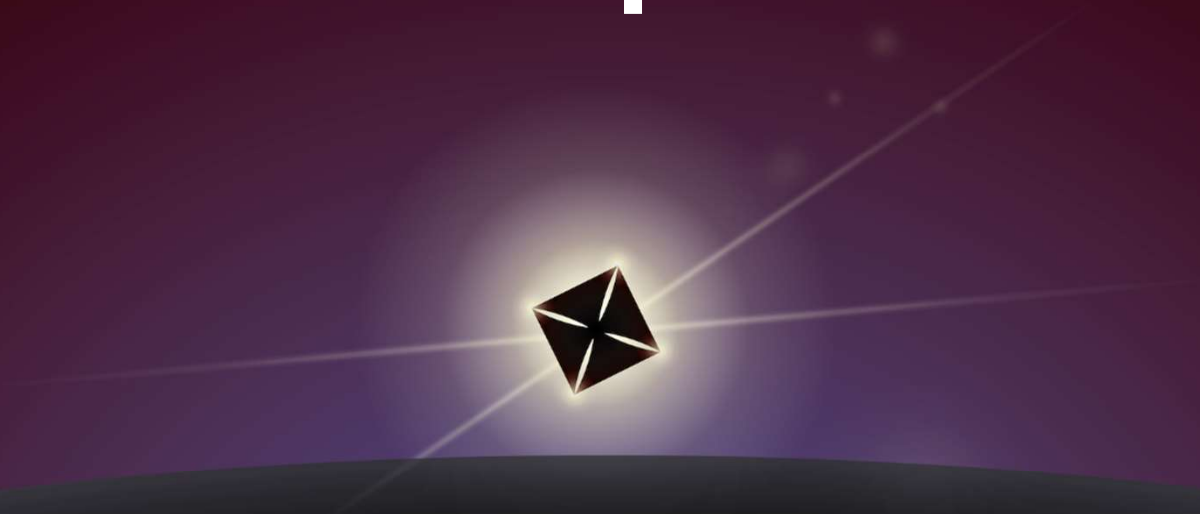


1st Prototype



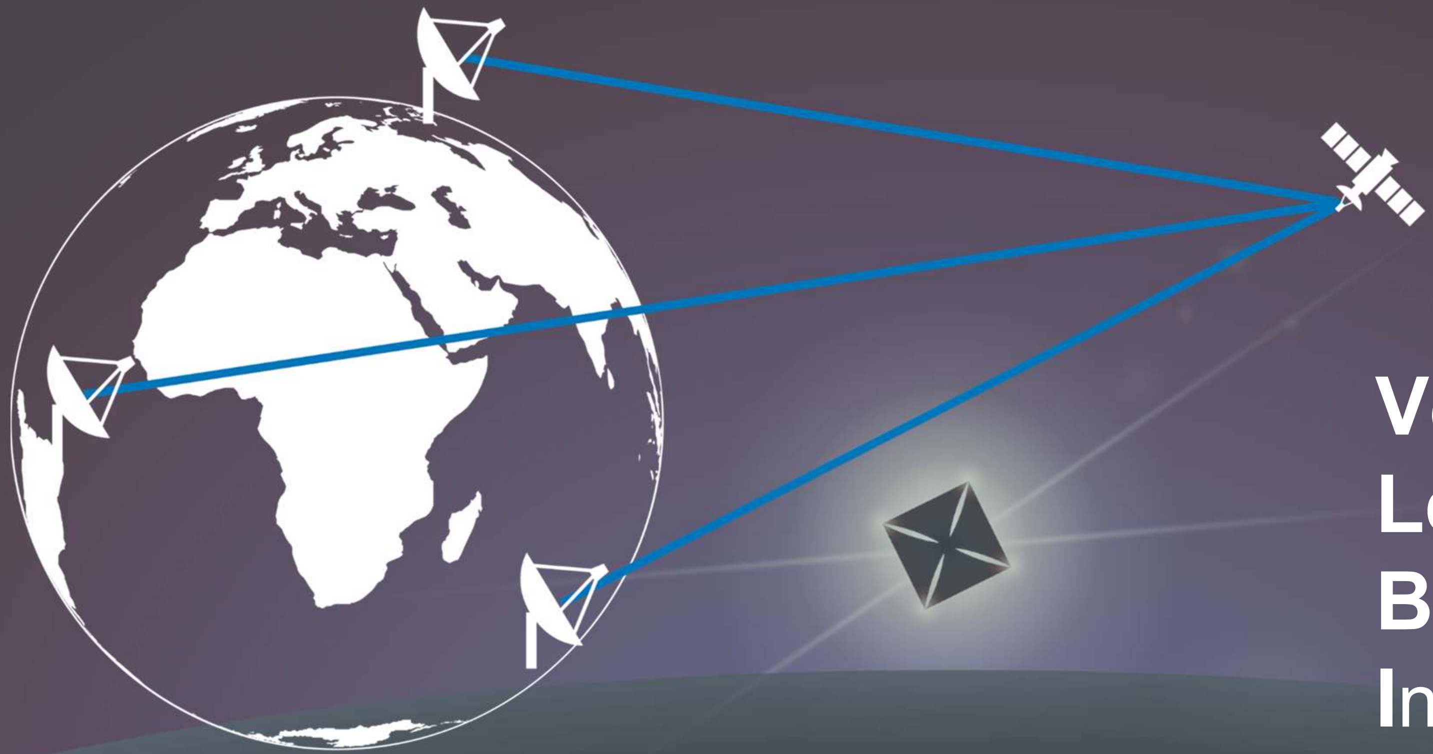
2nd Prototype

Mission Development



Tracking and Environmental Modelling

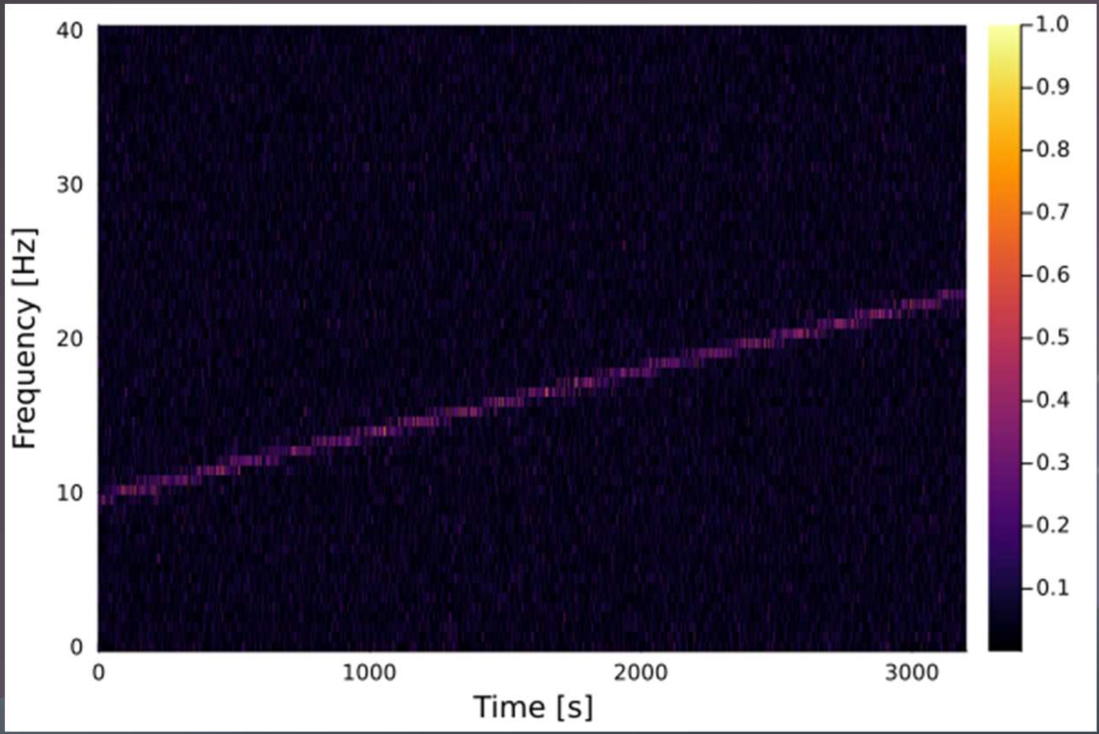
Tracking



Very
Long
Baseline
Interferometry

Tracking

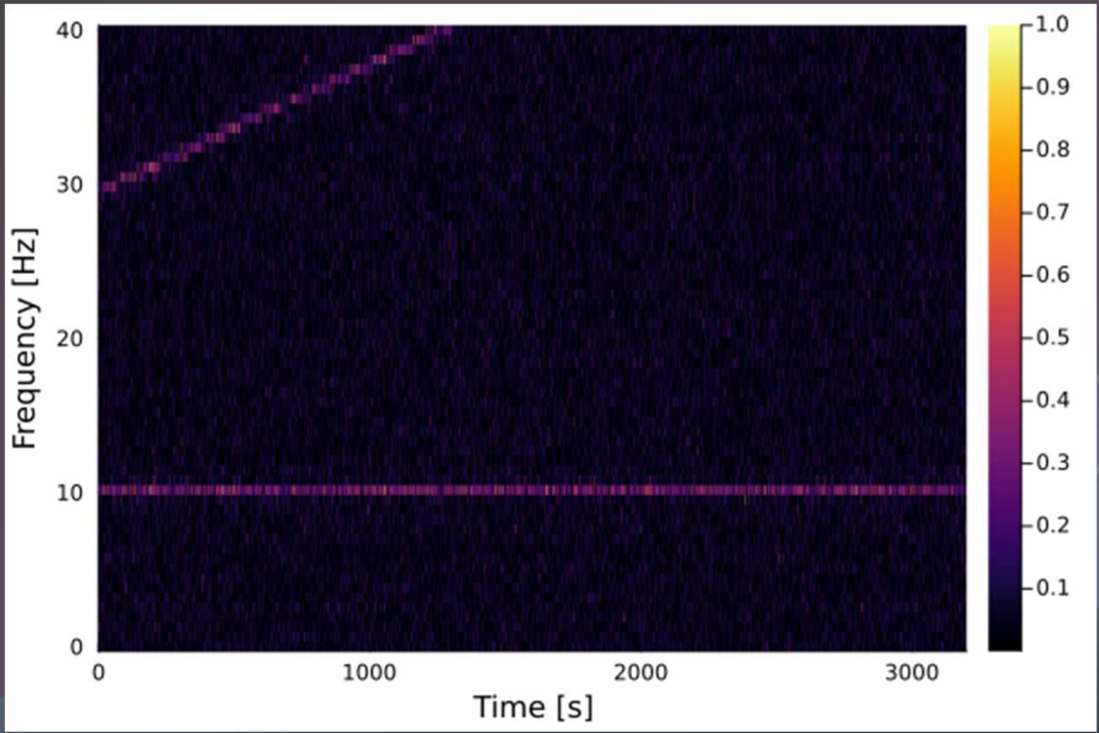
Simulated Data Stream



- Each data series in the waterfall plot is the Fourier transform of the signal over a one second sampling period.
- A non-linear regression is used to evaluate the best polynomial fit to the data.

Tracking

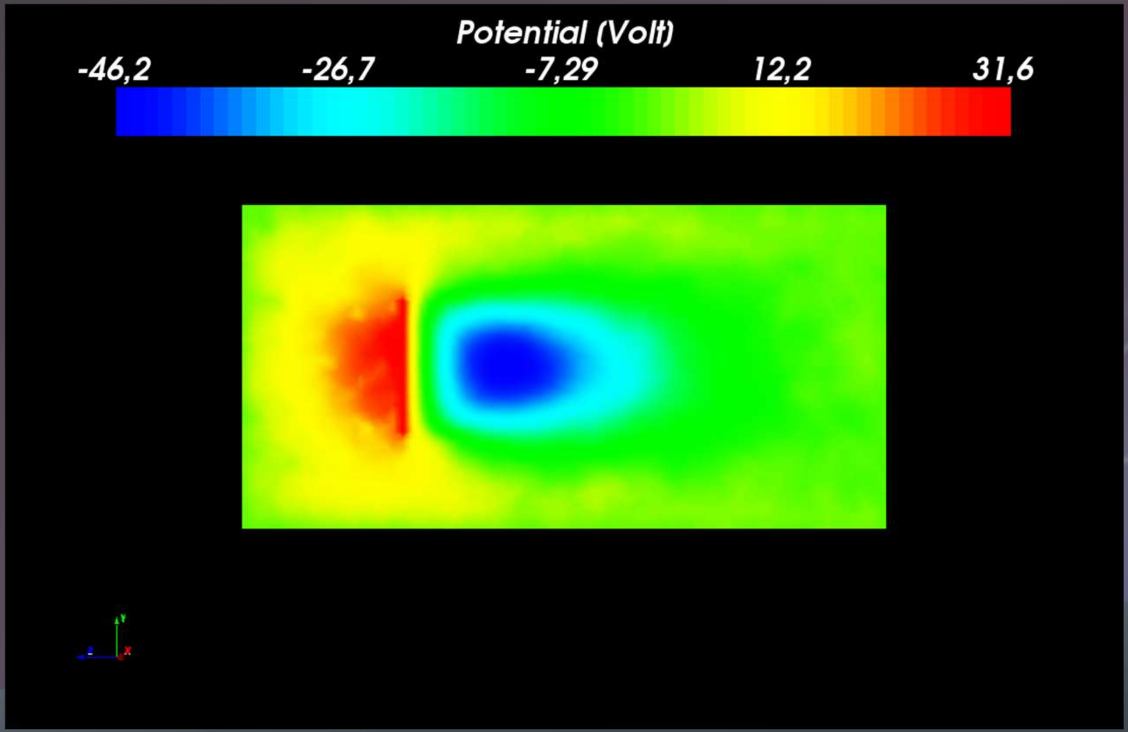
Corrected Data Stream



- The spectrum's phase shift is corrected to enable signal correlation.

Environmental Modelling

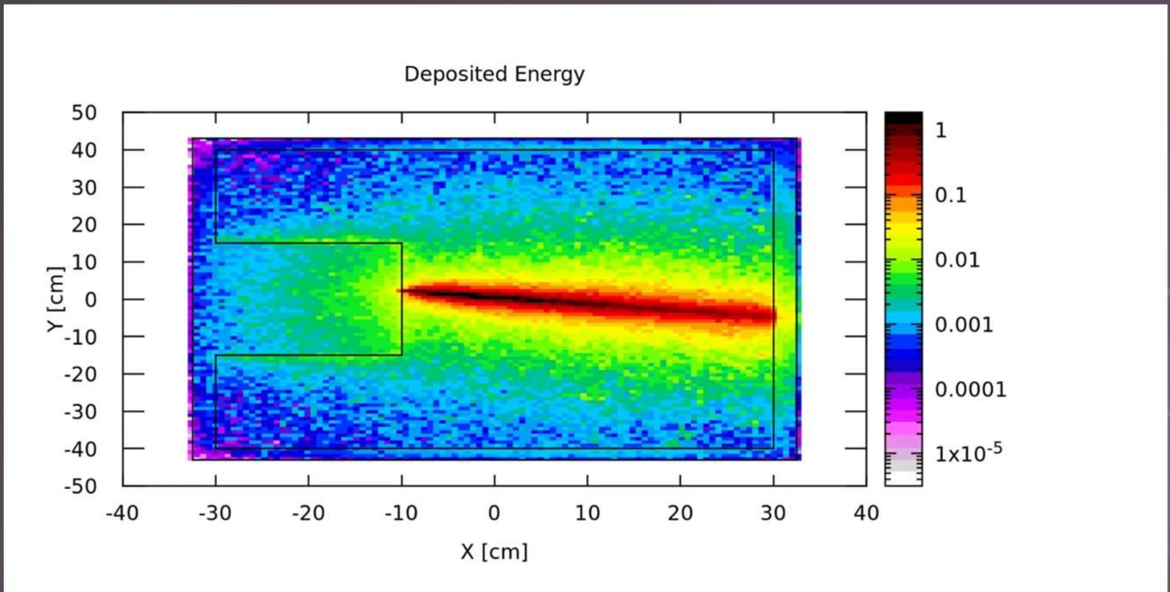
Spacecraft Charging



- Surface potential calculated using Particle-in-Cell model (SPIS) of solar wind with sail modelled as thin foil.
- Potential differences of order of 10 V for normal solar wind.
- During Carrington-class-event potential differences of up to 60 V.

Environmental Modelling

Radiation Dose



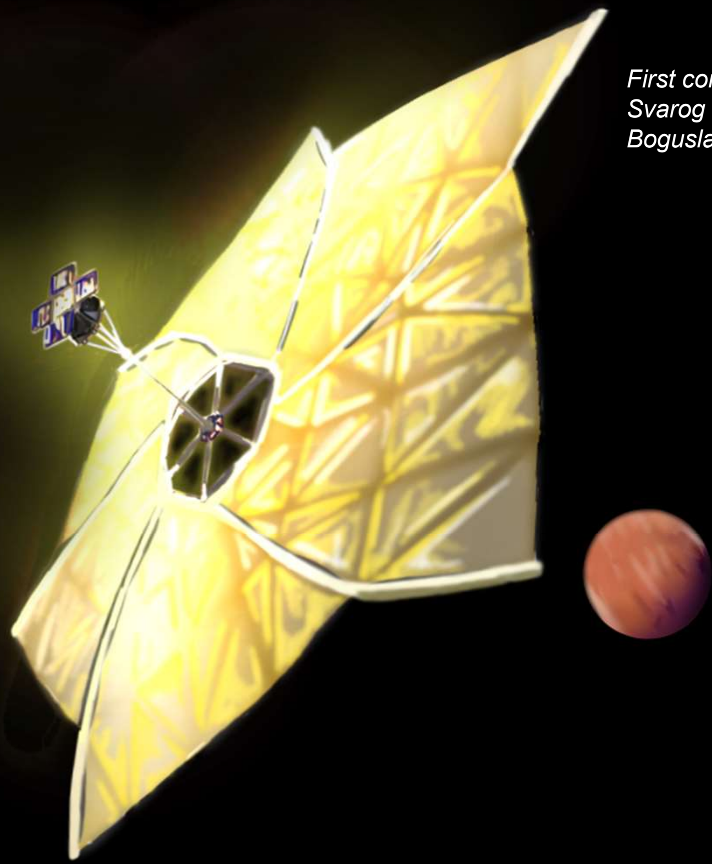
- Bethe-Bloch equation implemented with correction for high mass nuclei.
- Monte Carlo simulations using GEANT for validation.
- Design constrained by proton penetration depth.
- Validation required consideration of secondary neutrons.

Conclusions

Conclusions

The current goal is to define accurate technical requirements for the mission and further refine the following areas:

- Full analytical and numerical stability analysis of solar sail dynamics and investigation of coupling between different dynamic timescales.
- Further improvement of the non-dimensional analysis approach and extension to thick shells.
- Complete model of communication for validation of link budget and determination of potential reference sources for VLBI.
- Experimental testing of electronics in a radiation environment.
- Further development of boom deployment prototypes for testing and analysis.



First concept of Project Svarog in 2020 by Matvey Boguslavskiy

Thank you

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