Planetary Sunshade for Solar Geoengineering: *Sail Modelling and Configuration Selection*

Hollie Lumsden

BEng Aerospace Engineering, egyhl8@nottingham.ac.uk

University of Nottingham UK | CHINA | MALAYSIA

1. Abstract

Climate change is one of the biggest challenges of the 21st century, demanding solutions beyond emissions reduction alone. This project investigates the feasibility of a planetary sunshade designed to reduce the solar radiation reaching Earth. The research focuses on the design of a solar sail compatible with a 12U CubeSat platform. Several sail geometries, deployment mechanisms and folding strategies were evaluated using weighted decision matrices to identify the most suitable configuration. Modelling tools from the NASA Jet Propulsion Laboratory were then used to evaluate sail shading performance and compared to the matrix results.

2. Background

Global climate change remains a critical challenge, with 2024 recorded as the warmest year in a 175-year record. This temperature rise is primarily driven by greenhouse gas emissions, leading to increasingly severe global disasters and highlighting the urgent need for the removal of excess CO_2 from the atmosphere. Current proposed solutions include Carbon Dioxide Removal (CDR), which focuses on actively removing CO_2 from the atmosphere, and Solar Radiation Modification (SRM), which aims to reduce the amount of solar energy reaching Earth. Key SRM approaches include stratospheric aerosol injection and the planetary sunshade concept.

3. Current Proposed Roadmap

C. L. Matonti et al., "Roadmap Toward a Planetary Sunshade for Space-Based Solar Geoengineering,"

Phase 1 2025 → Early-technology testing and precursor limited deployment

Phase 2 2040 → Enhanced operational capability and monitoring climate outcomes of Earth

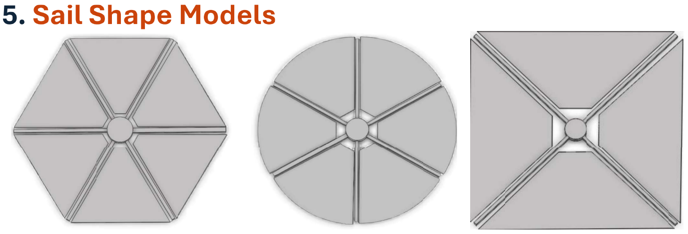
Phase 3 2070 → Fully operational phase including end-of-life operations, whilst also mitigating and monitoring climate change effects

4. Aims and Objectives

The aim of this project is to analyse and compare different sail shapes and evaluate their performances through a specific software (from NASA Jet Propulsion Lab) to optimise planetary sunshade effectiveness in reducing climate change on Earth

- ★ To define and consolidate the mission and system requirements
- ★ To design and develop a CAD model of the Planetary Sunshade (12U CubeSat and its sail)
- ★ To analyse the benefits and drawbacks of various sail shapes
- ★ To analyse the benefits and drawbacks of different shadowing solutions (transmissive, reflective, refractive)
- ★ To use JPL's code to compare and analyse the results of the different shadows obtained by the various sail shapes
- ★ To select the best sail configuration to optimise the Solar Radiation Modification (SRM) effect

5. Sail Shape Models



The above are CAD renders of possible configurations for the planetary sunshade sail: hexagonal, circular, and square. Each design has a central circular hub (where the booms and sail would be stored during launch) and booms for supporting each sail segment. The areas of each sail were kept similar to help with analysis.

6. Initial Design Decisions

Weighted decision matrices were used to assess sail shape, deployment, and folding mechanisms for the planetary sunshade. These decisions were to be then compared with the JPL results to select the final sail shape.

Sail Shape	Deployment Mechanism	Folding Mechanism
Hexagon	Spinning	Spiral Roll
★ Strong shading efficiency ★ High structural performance ★ Good modularity	★ High reliability ★ Low complexity ★ Compact storage	★ Good packing efficiency ★ Reliable deployment

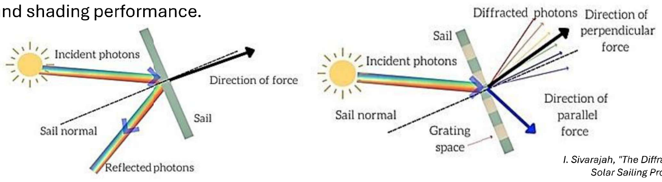
7. Planetary Sunshade CAD Model

8. Sail Shadowing Solutions

Two sail architectures were evaluated: reflective and transmissive solar sails.

Reflective Sails	Transmissive Sails
Advantages	
★ technologically mature ★ generate thrust via photon reflection ★ demonstrated in missions (IKAROS, NanoSail-D, LightSail 1)	★ use refraction or diffraction to remain Sun-facing to maximise shading and decoupling thrust from performance
Disadvantages	
★ require tilting that reduces shading efficiency	★ remain experimental with lower technology readiness

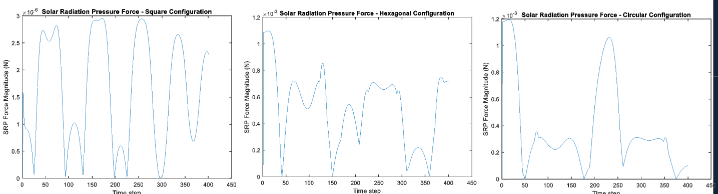
Reflective sails are suited to near-term missions, while transmissive sails offer greater long-term potential, with final selection dependent on the trade-off between maturity and shading performance.



I. Sivarajah, "The Diffractive Solar Sailing Project,"

9. NASA JPL MuSCAT Code

MUSCAT, an open-source NASA JPL tool for low-fidelity spacecraft simulations, used to compare shadows from square, hexagonal, and circular sunshade sails. It was chosen for its ability to model solar radiation pressure (SRP) on custom geometries.



The above graphs of SRP force magnitude against time step for the square, hexagon and circular configurations give the mean force applied to each sail.

Mean Applied SRP Force		
Square	Hexagonal	Circular
$1.6226 \times 10^{-6}\ N$	$5.1664 \times 10^{-4}\ N$	$3.8747 \times 10^{-4}\ N$

This agrees with the initial design decisions done previously, where the hexagonal configuration came out best, as the mean SRP force is the highest.

10. Conclusion

This project investigated and compared solar sail configurations for a CubeSat-based planetary sunshade. CAD modelling and decision matrices were used to evaluate design options where the hexagonal sail was identified as the optimal sail geometry, while the spinning deployment mechanism and spiral folding method provided the most effective and reliable deployment solution within CubeSat constraints. A comparison of reflective and transmissive sail architectures highlighted a trade-off between technological maturity and shading performance. Simulation using NASA JPL's MuSCAT tool demonstrated that sail geometry directly influences solar radiation pressure and therefore shading effectiveness, and that the simulation agreed with the decision matrices done previously. Overall, this work provides a preliminary design and supports precursor missions for further development towards large-scale planetary sunshade deployment.

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