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MASTER's Degree in AEROSPACE ENGINEERING

Conceptual Design and Feasibility Assessment of Deployable Reflective Membrane Arrays for Space-Based Solar Radiation Management

Master's Thesis

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Abstract

Climate change represents one of the most significant global challenges of the twenty-first century, motivating the investigation of innovative approaches capable of complementing conventional greenhouse gas mitigation strategies. Among the various geoengineering concepts proposed in recent decades, Space-Based Solar Radiation Management (SB-SRM) has emerged as a potential long-term solution aimed at reducing the amount of solar radiation reaching the Earth through dedicated space infrastructures. This thesis investigates the potential application of Deployable Reflective Membrane Arrays as a candidate architecture for Space-Based Solar Radiation Management operating near the Sun-Earth L1 Lagrange point. The work begins with an overview of space sails and deployable membrane technologies, including solar sails, solar power sails, electric sails, magnetic sails, drag sails, deployable membrane antennas, and other large-area membrane systems. Particular attention is devoted to Deployable Membrane Reflectors (DMRs), focusing on their operating principles, membrane materials, deployment mechanisms, structural architectures, and technological heritage. The analysis highlights the role of lightweight deployable structures in enabling large functional surfaces while maintaining low mass and compact launch configurations. Building upon this technological background, a review of Space-Based Solar Radiation Management concepts proposed in the literature is performed. Candidate architectures, including monolithic sunshades, distributed particle clouds, spacecraft swarms, and membrane-based systems, are analysed to identify their principal advantages, limitations, and technological requirements. A structured trade-off process is subsequently conducted to evaluate the different concepts according to mission-oriented criteria such as effectiveness, scalability, technological maturity, deployment complexity, and operational robustness. The selected architecture is then developed through a preliminary mission design process. Mission objectives, orbit selection, membrane sizing methodologies, spacecraft configuration, deployment strategies, structural layouts, and formation architectures are defined at a conceptual level. Particular emphasis is placed on the integration of deployable membrane technologies, support structures, and attitude-control systems within a distributed spacecraft architecture operating near the Sun–Earth L1 point. The final part of the thesis focuses on the engineering feasibility of the proposed concept. Preliminary mass and power budgets are established, launch and deployment requirements are examined, station-keeping considerations are discussed, and the maturity of the enabling technologies is assessed. In addition, the principal challenges associated with large-scale membrane deployment, structural stability, autonomous formation control, manufacturing scalability, and long-term operation in the space environment are identified. Through this multidisciplinary analysis, the thesis provides a preliminary framework for the assessment of Deployable Reflective Membrane Arrays as a potential enabling technology for future Space-Based Solar Radiation Management systems and establishes a foundation for further investigations into large-scale space-based climate mitigation infrastructures.

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Introduction

1.1 Structure of the Thesis

This thesis is organized into six chapters, each addressing a specific aspect of the investigation of Deployable Reflective Membrane (DRM) as a potential Space-Based Solar Radiation Management (SB-SRM) solution operating near the Sun–Earth L1 point to mitigate Climate change.

The structure of this study is as follows:

- **Chapter 1: Introduction** – This chapter introduces the global challenge of climate change and provides an overview of different geoengineering approaches, with particular emphasis on Space-Based Solar Radiation Management. Then the objectives and scope of the thesis will be presented;
- **Chapter 2: Space Sails and Deployable Membrane Reflectors** – This chapter presents the actual state of the art in deployable membrane technologies. Different categories of space sails, including solar sails, electric sails, and magnetic sails are presented. An entire section is dedicated to deployable membrane reflectors, their operating principles, deployment mechanisms, structural characteristics, and relevant technology demonstrators;
- **Chapter 3: Deployable Membrane Reflectors: Architecture and Deployment Mechanism** - This chapter focuses on the structural design of Deployable Membrane Reflectors. The architecture of a typical DMR is first presented by analysing its main systems, including the reflective membrane, supporting structures, deployment mechanisms, and spacecraft bus. The chapter then reviews membrane materials, deployable boom technologies, deployment architectures, and the structural behaviour of large membrane systems. Finally, a technology trade-off is performed to define the baseline configuration adopted for the proposed mission.
- **Chapter 4: Trade-Off Analysis & Mission Concept Selection** – This chapter develops a systematic trade-off process for the evaluation of candidate Space-Based Solar Radiation Management architectures. Mission drivers, evaluation criteria, and candidate concepts derived from concepts or existing missions are analyzed in order to identify the most suitable architecture. The chapter concludes with the selection of a DRM concept and the definition of the corresponding high-level mission requirements;
- **Chapter 5: Preliminary Mission Design** – Based on the selected concept, this part develops the preliminary mission architecture. The analysis includes mission objectives, orbit selection, membrane sizing methodology, spacecraft configuration, deployment strategy, formation architecture, and operational concept. Particular attention is given to the use of displaced non-Keplerian orbits near the Sun–Earth L1 point;
- **Chapter 6: Conclusions and Future Work** – The final chapter summarizes the main results of this study, highlights its main contributions, discusses the limitations of the study, and outlines future research directions required to advance the development of large-scale deployable membrane systems for space-based climate mitigation applications.

The study follows a progressive systems engineering approach. Starting from the analysis of existing technologies and concepts, the study proceeds through concept selection, preliminary mission design, and

feasibility assessment, ultimately providing a structured framework for evaluating Deployable Reflective Membranes as a potential long-term solution for Space-Based Solar Radiation Management.

1.2 Introduction to Climate Change

Climate change is widely recognized as one of the most critical challenges facing humanity in the twenty-first century. Over the past two centuries, rapid industrialization, population growth, and the extensive use of fossil fuels have profoundly altered the composition of the Earth's atmosphere, resulting in significant modifications of the global climate system. The consequences of these changes are increasingly evident through rising global temperatures, more frequent extreme weather events, rising sea level, and widespread impacts on natural ecosystems and human societies.

The Earth's climate is governed by a complex energy balance between incoming solar radiation and outgoing thermal radiation (see figure 1.1).

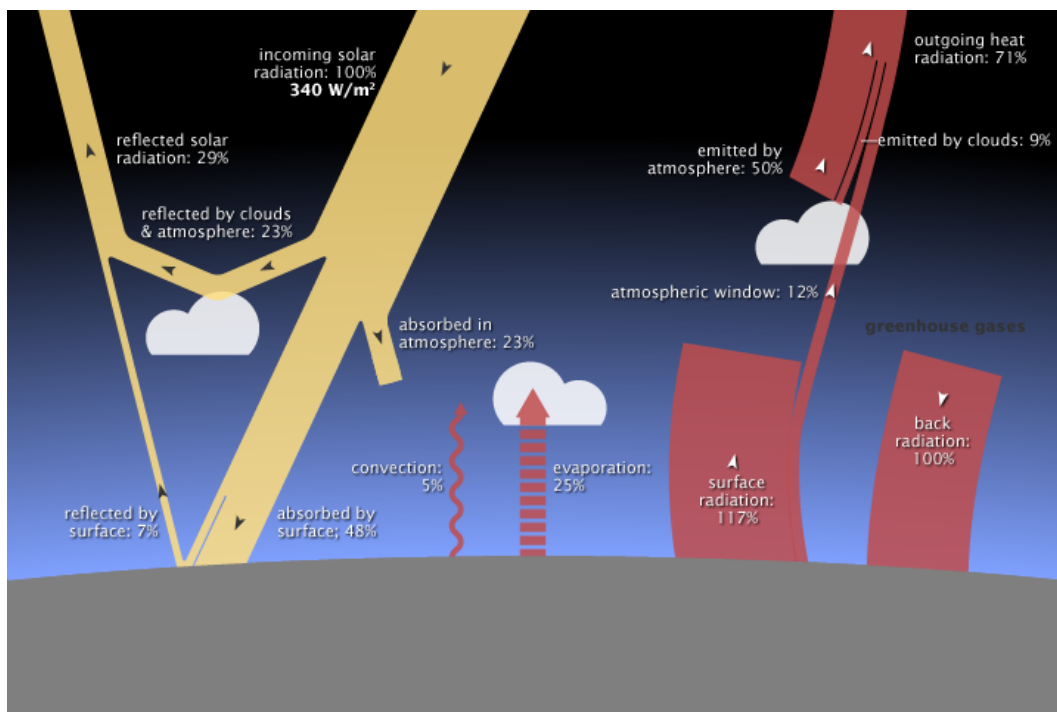


Figure 1.1: Simplified representation of the Earth's energy balance and greenhouse effect. Incoming solar radiation is partially reflected by the atmosphere and Earth's surface, while absorbed energy is re-emitted as infrared radiation. Greenhouse gases absorb and re-radiate part of this outgoing energy, contributing to surface warming. Adapted from NASA Earth Observatory[18].

Solar energy reaches the Earth primarily in the form of shortwave radiation. A portion of this energy is reflected back into space by clouds, atmospheric particles, ice-covered regions, and highly reflective surfaces, while the remainder is absorbed by the atmosphere, oceans, and land masses. In turn, the Earth emits thermal infrared radiation toward space in order to maintain radiative equilibrium.

Naturally occurring greenhouse gases play a fundamental role in regulating this energy balance. Molecules such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and water vapor absorb part of the outgoing infrared radiation and re-emit it in all directions, trapping heat within the atmosphere. This natural greenhouse effect increases the average surface temperature of the Earth from approximately -18°C to about 15°C , making life as we know it possible.

However, since the beginning of the Industrial Revolution, human activities have substantially increased atmospheric concentrations of greenhouse gases. Carbon dioxide concentrations have risen from approximately

280 ppm in pre-industrial times to more than 420 ppm today. In figure 1.2 the results of the increasing of concentration of dioxide measured by Manua Loa Observatory are presented. Similar trends have been observed for methane and nitrous oxide. The resulting enhancement of the greenhouse effect has generated a positive radiative forcing, producing an imbalance between incoming and outgoing energy fluxes and leading to a gradual increase in global temperatures.

ATMOSPHERIC CARBON DIOXIDE

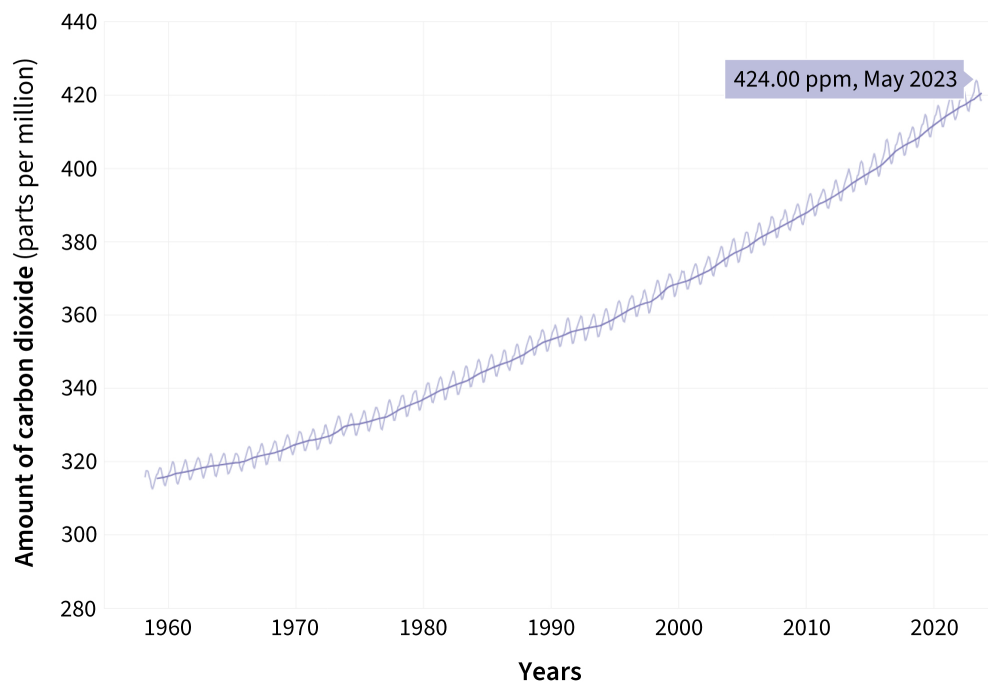


Figure 1.2: Evolution of atmospheric carbon dioxide concentration measured at the Mauna Loa Observatory. The long-term increase reflects anthropogenic emissions from fossil fuel combustion and land-use changes. Credits: NOAA Global Monitoring Laboratory[25].

According to the latest assessment reports of the Intergovernmental Panel on Climate Change (IPCC)[44], global average surface temperature has already increased by approximately 1.1°C relative to pre-industrial levels. Scientific observations indicate that the warming trend is accelerating and is accompanied by a wide range of environmental consequences, including glacier reat, reductions in Arctic sea ice extent, increasing ocean temperatures, biodiversity loss, and changes in precipitation patterns.

The growing severity of climate-related impacts has motivated governments, international organizations, and the scientific community to investigate strategies capable of limiting future warming and stabilizing the Earth's climate system.

1.3 Current mitigation strategies and their limitations

The first response to climate change has traditionally focused on mitigation, namely the reduction of greenhouse gas emissions at their source. Mitigation strategies include the deployment of renewable energy technologies, improvements in energy efficiency, electrification of transportation systems, industrial decarbonization, and sustainable land-use practices.

International agreements such as the Paris Agreement have established ambitious targets aimed at limiting global warming to well below 2°C while pursuing efforts to maintain temperature increases below 1.5°C . Achieving these objectives requires rapid reductions in global emissions over the coming decades.

Despite significant technological progress, several factors complicate the achievement of these targets. First, the global energy system remains heavily dependent on fossil fuels. Second, many industrial sectors such as aviation, shipping, steel production, and cement manufacturing remain difficult to decarbonize completely. Finally, the long atmospheric lifetime of carbon dioxide implies that a substantial fraction of previously emitted CO₂ will remain in the atmosphere for centuries.

Climate projections suggest that even aggressive mitigation measures may not be sufficient to prevent temporary exceedance of critical temperature thresholds. Consequently, in the last decades attention has been directed toward complementary approaches capable of reducing atmospheric greenhouse gas concentrations or directly modifying the Earth's radiative balance.

1.4 Geoengineering as a climate intervention strategy

Geoengineering can be described as the science that deliberate large-scale intervention in the Earth's climate system with the objective of counteracting anthropogenic climate change. Although geoengineering cannot replace conventional mitigation policies, it is increasingly being investigated as a potential complementary strategy to reduce climate consequences[24].

Geoengineering approaches are generally classified into two major categories:

1. **Carbon Dioxide Removal (CDR);**
2. **Solar Radiation Management (SRM).**

Fundamentally, the difference between these approaches is related to their operating principles and their effects on the climate system.

1.4.1 Carbon Dioxide Removal

Carbon Dioxide Removal incls a broad range of technologies aimed to reduce atmospheric concentrations of carbon dioxide by actively removing CO₂ from the atmosphere and storing it over long timescales.

Unlike SRM, CDR directly addresses the root cause of anthropogenic climate change by reducing greenhouse gas concentrations. As a result, it contributes not only to the stabilization of temperature but also to mitigating other consequences of elevated CO₂ levels, such as ocean acidification.

Several CDR technologies have been proposed and investigated:

- Afforestation and reforestation;
- Bioenergy with Carbon Capture and Storage (BECCS);
- Direct Air Capture (DAC);
- Enhanced weathering;
- Ocean fertilization;
- Biochar production.

Among these approaches, Direct Air Capture has received significant attention due to its flexibility and scalability. DAC systems employ chemical processes capable of extracting carbon dioxide directly from ambient air before compressing and storing it in geological reservoirs.

Although CDR technologies offer substantial long-term benefits, they also face significant challenges. Large-scale deployment requires considerable energy resources, extensive infrastructure, and substantial financial investments. Furthermore, the quantities of CO₂ that must be removed to significantly affect global climate trends are extremely large, often measured in gigatons per year.

For these reasons, CDR is generally considered a long-term climate stabilization strategy rather than a mechanism capable of rapidly reducing global temperatures.

1.4.2 Solar Radiation Management

Solar Radiation Management concerns a set of techniques designed to reduce the amount of solar energy absorbed by the Earth system. Instead of removing greenhouse gases from the atmosphere, SRM seeks to compensate for their warming effect by increasing planetary reflectivity or reducing incoming solar radiation.

The fundamental principle is based on modifying the Earth's radiative balance to counteract positive radiative forcing generated by greenhouse gas accumulation.

Several SRM concepts have been proposed, as:

- Stratospheric Aerosol Injection;
- Marine Cloud Brightening;
- Cirrus Cloud Thinning;
- Surface Albedo Modification;
- Space-Based Solar Shields.

One of the most extensively studied approaches is Stratospheric Aerosol Injection, which consists of dispersing reflective particles into the stratosphere to increase the reflection of sunlight back into space. The concept is inspired by natural cooling effects observed after major volcanic eruptions.

The principal advantage of SRM is the potential for a relatively rapid climatic response. Climate simulations suggest that global temperatures could be reduced within years rather than decades. However, SRM does not address atmospheric greenhouse gas concentrations and therefore cannot solve associated problems such as ocean acidification.

Furthermore, uncertainties remain regarding possible side effects, including alterations in precipitation patterns, regional climate disruptions, and governance challenges associated with global-scale climate interventions.

1.5 Space-Based geoengineering

Among the previous Solar Radiation Management approaches, space-based geoengineering represents one of the most ambitious and technologically challenging concepts.

The fundamental objective of space-based geoengineering is to intercept a fraction of incoming solar radiation before it reaches the Earth's atmosphere. By reducing the solar energy entering the climate system, it becomes theoretically possible to compensate for a significant portion of anthropogenic radiative forcing.

Unlike atmospheric SRM techniques, space-based systems operate outside the Earth's atmosphere and therefore avoid direct chemical interactions with atmospheric constituents. This characteristic potentially reduces some of the environmental risks and effects associated with alternative geoengineering methods.

The concept was initially proposed several decades ago and has since evolved alongside advances in space engineering, materials science, and orbital mechanics.

1.5.1 Space sunshades at the Sun-Earth L1 Point

One of the most widely studied concepts involves positioning large numbers of lightweight structures near the Sun-Earth Lagrange Point L1. As we can see in figure 1.3, there are different Lagrange points and they are positions in space where the gravitational forces of a two body system like the Sun and the Earth produce enhanced regions of attraction and repulsion. These can be used by spacecraft to reduce fuel consumption needed to remain stable in position and in that orbit.

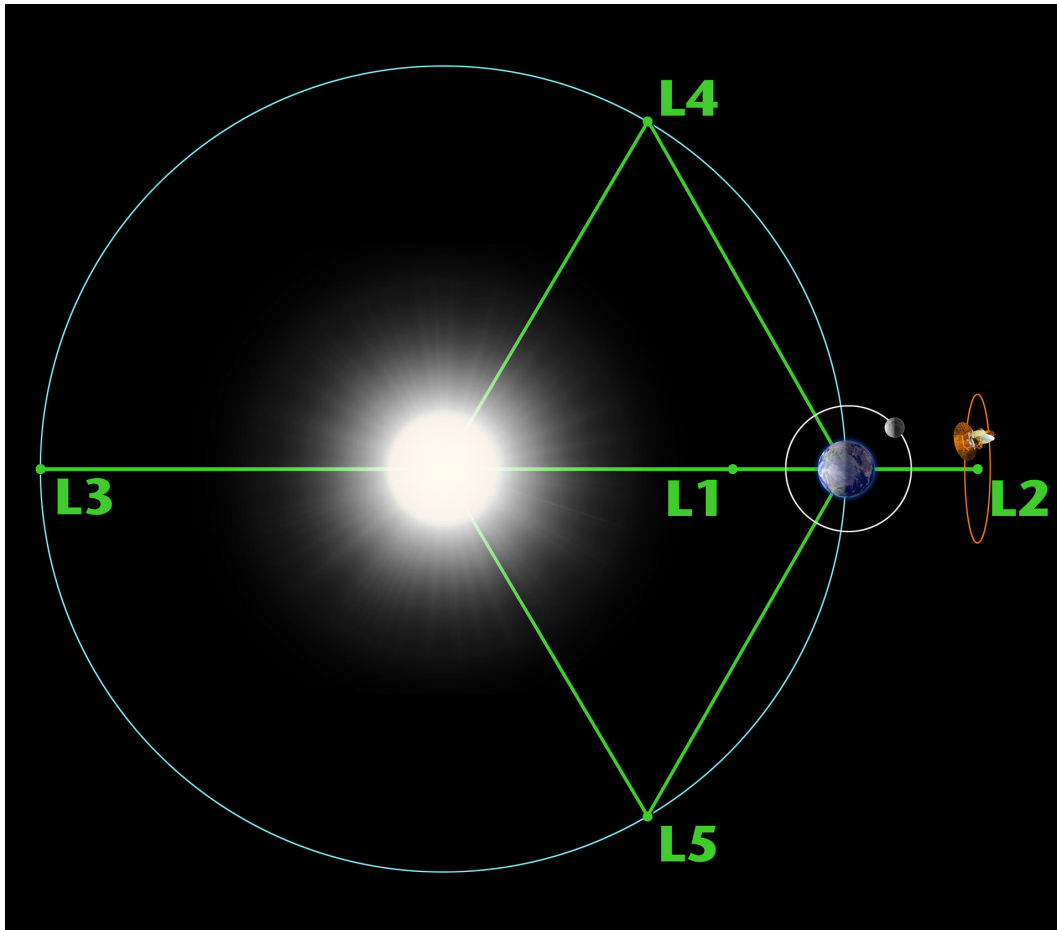


Figure 1.3: Location of the Sun-Earth L1 Lagrange point. The point lies approximately 1.5 million kilometers from Earth toward the Sun and represents a favorable location for solar-shielding systems. Credits: ESA[47].

The L1 point is located approximately 1.5 million kilometers from Earth along the Earth-Sun line. At this location, gravitational forces and orbital dynamics create conditions that allow spacecraft to remain relatively close to the Earth-Sun axis with limited station-keeping requirements.

The concept proposed by Angel[14] envisioned a vast fleet of ultra-light spacecraft capable of collectively reducing incoming solar irradiance by approximately 1-2% , sufficient to offset a significant fraction of anthropogenic warming.

Rather than relying on a single massive structure, distributed architectures offer greater redundancy, scalability, and resilience against failures.

1.5.2 Deployable Membrane Reflectors

Among the various space-based concepts, Deployable membrane reflectors or reflective membrane systems have emerged as particularly attractive from an aerospace engineering perspective.

These systems consist of extremely thin and lightweight membranes designed to reflect, refract, or redirect incoming solar radiation away from the Earth. Advances in thin-film materials and solar sail technologies have significantly improved the feasibility of manufacturing such structures.

Reflective membranes offer several advantages:

- Very low areal density;
- Scalability through modular deployment;
- Compatibility with existing solar sail technologies;

- Potential exploitation of solar radiation pressure for attitude control and station keeping.

The lightweight nature of this systems substantially reduces launch mass requirements compared to conventional rigid structures, making them among the most promising candidates for future space-based climate intervention systems. In the next chapters we will analyze the compatibility with solar sails membrane, especially with successful missions like Lightsail by The Planetary Society[39]. This mission, in fact, represents an innovative approach to space mission using solar radiation as propulsion deploying the entire membrane sail that measures 5.6 meter for side (see fig.1.4).

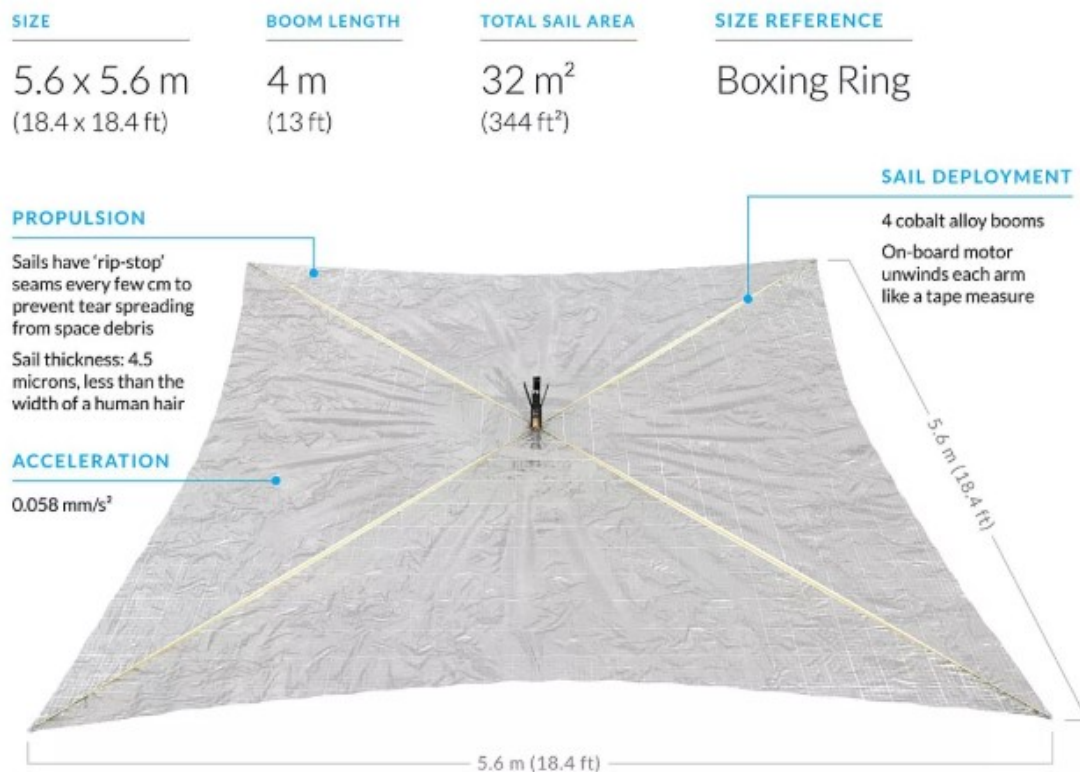


Figure 1.4: LightSail Solar sail specs. Credits: The Planetary Exploration[39].

1.5.3 Alternative Concepts

Other proposed approaches include the creation of artificial dust clouds using material extracted from asteroids or lunar resources. Such particles would form a diffuse solar shield capable of scattering a fraction of incoming sunlight.

Although potentially reducing manufacturing requirements, these concepts introduce additional challenges related to orbital stability, particle dispersion control, and long-term maintenance.

Consequently, engineered membrane systems remain among the most mature and technically analyzable solutions currently proposed in the literature.

1.6 Objectives and Scope of the Thesis

Among the various space-based geoengineering concepts proposed in the literature, deployable membrane reflectors represent one of the most promising solutions due to their low mass, scalability, and compatibility with existing aerospace technologies.

The performance of such systems depends strongly on mission design parameters, including orbital location, deployment architecture, optical properties of the membrane, attitude control strategies, and station maintenance requirements.

For this reason, the present study focuses on the preliminary design and analysis of a space-based sunshield system based on reflective membranes operating within the Sun-Earth system.

The following chapters investigate the mission-design aspects associated with the deployment of reflective membrane structures. Particular attention will be devoted to trajectory design, orbital dynamics near the Sun-Earth L1 region, sizing considerations, deployment strategies, and overall system performance.

The ultimate objective is to evaluate the technical feasibility of reflective membrane solar shields as a potential long-term contribution to climate change mitigation, combining climate intervention objectives with advanced aerospace engineering methodologies.

Space Sails and Deployable Membrane Reflectors

2.1 Introduction to Space Sails

Space sails represent an innovative approach to spacecraft propulsion, making possible missions that are not limited by onboard propellant.

These space systems exploit the transfer of momentum from external sources, primarily solar photons[30], but also laser beams[48] or charged particles to generate continuous low-thrust acceleration over long periods of time, such as electric[33] and magnetic fields[20]. Although thrust levels are smaller than the other propulsion systems, such as chemical propulsion, the absence of propellant consumption allows space sails to achieve very high velocities over extended mission durations using it as auxiliary propulsion, both for missions near Earth[23] and deep space[38].

The operating principle of space sails is the radiation pressure. Photons, despite having no rest mass, carry momentum when they are reflected or absorbed by a surface, they produce a force. For a perfectly reflecting surface, the radiation pressure can be expressed as:

$$P = \frac{2I}{c} \quad (2.1)$$

where I is the incident radiation intensity and c is the speed of light. At 1 AU, the solar radiation pressure is approximately $9 \mu\text{N}/\text{m}^2$, which is extremely small but sufficient for propulsion when applied to very large and lightweight surfaces.

Another characteristic of space sails is their extremely low areal density, typically on the order of a few grams per square meter or less. This is achieved through the use of ultra-thin polymer films (such as Kapton or Mylar) coated with reflective materials like aluminum. As it will be described in the next chapters, the structural design must balance different requirements, like:

- High reflectivity to maximize momentum transfer;
- Low mass to increase acceleration;
- High thermal resistivity to withstand solar radiation;
- Mechanical robustness to survive deployment and micrometeoroid impacts.

In addition to propulsion, space sails are also related to a broader class of deployable membrane structures used for power generation, communications, and thermal control, like deployable solar array[32].

There are many apparent synergies between different types of space sail, with room to be cultivated further.

The main types of space sails can be classified as:

- Solar sail;

- Laser-driven sail;
- Drag sail;
- Electric sail;
- Magnetic sail;
- Deployable membrane reflector;
- Deployable membrane antenna
- Solar power sail.

In figure 2.1 different projects and mission concepts are presented for each group of space sails. Some have been flight tested with operational heritage, while some remain at the concept stage, planned to reach maturity in the coming decades. Against this backdrop, it is time to recognise the advantages of space sails for supporting the achievement of a wide range of space exploration goals[46].

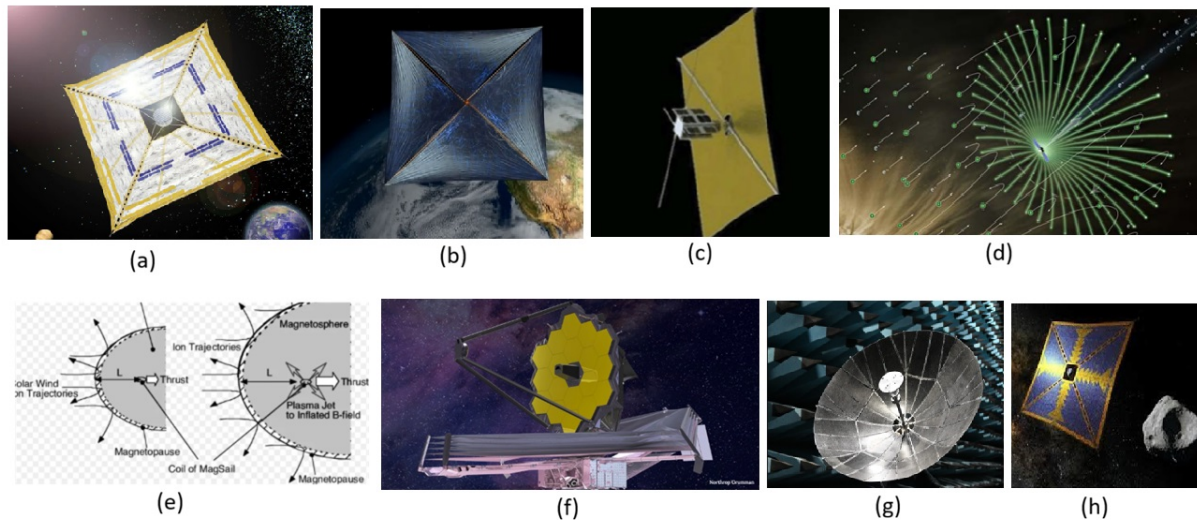


Figure 2.1: Concepts or on going mission of different space sails:

(a) Solar sail: IKAROS[27]; (b) Laser-driven sail: Breakthrough Starshot[48]; (c) Drag sail De-Orbit Mechanism (DOM)[49]; (d) Electric sail: E-sail[13]; (e) Magnetic sail: Magnetoplasma Sail (MPS)[11]; (f) Deployable membrane reflector: JWST sunshade[43]; (g) Deployable membrane antenna: Inflatable Antenna Experiment (IAE)[4]; (h) Solar power sail: OKEANOS[38].

The common denominator of all space sails is the use of deployable membrane technologies. Large ultra-thin membranes, lightweight support structures, and compact deployment systems enable sail areas ranging from tens to thousands of square metres while remaining compatible with current launch vehicle fairings. Consequently, the technological evolution of space sails has driven substantial advances in membrane materials, composite deployable booms, folding techniques, structural dynamics, and autonomous deployment mechanisms. These developments have progressively transformed solar sailing from a theoretical concept into a flight-demonstrated technology and have simultaneously established the technological foundations for many other deployable membrane applications [9].

Although these concepts differ considerably in terms of operating principles and technological maturity, they all rely on lightweight deployable structures and membrane engineering. Consequently, research carried out in the field of space sails has significantly contributed to the advancement of deployable membrane technologies that are now employed in numerous space applications.

Among these applications, Deployable Membrane Reflectors (DMRs) have recently attracted growing interest because they exploit many of the same structural technologies while serving purposes beyond propulsion, including communication systems, optical payloads, thermal control, and Space-Based Solar Radiation Management. For this reason, a brief overview of other membrane-based space systems is presented in the following section before focusing on Deployable Membrane Reflectors, which constitute the main technological subject of this thesis.

2.1.1 Solar Sails

Solar sails are the most mature and widely studied type of space sail. The concept dates back to the early 17th century with Johannes Kepler, who observed that comet tails are pushed away from the Sun. The modern theoretical foundation was developed in the 20th century by pioneers such as Konstantin Tsiolkovsky and Friedrich Zander, who first proposed the use of light pressure for propulsion[26].

In the last few decades, solar sail technology has experienced a significant resurgence due to advances in lightweight materials, deployable structures, and CubeSat platforms. This renewed interest has led to a series of experimental and demonstration missions that have progressively validated the concept in operational space environments.

These developments demonstrate that solar sailing has transitioned from a primarily theoretical propulsion concept to a maturing experimental technology, with increasing relevance for deep-space exploration architectures in the coming decades.

Significant experimental milestones missions include:

- **IKAROS** (JAXA, 2010)[27]: Demonstrated interplanetary solar sailing and attitude control using reflectivity modulation;
- **NanoSail-D** (NASA, 2010)[22]: Validated deployment technologies for compact sails in low Earth orbit;
- **LightSail 2** (The Planetary Society 2019)[39]: Demonstrated controlled solar sailing in Earth orbit using a CubeSat platform.

More recently, NASA has accelerated research through technology demonstrators such as the *NEA Scout* mission[37] (launched in 2022 as part of the Artemis 1 mission), which aimed to perform a near-Earth asteroid flyby using a solar sail as primary propulsion, and the *Advanced Composite Solar Sail System (ACS3)*[40] launched in 2024. ACS3 focuses on the validating next-generation composite deployable booms and scalable sail architectures, enabling future sails with areas up to thousands of square meters.

In addition to these missions, several ambitious mission concepts remain under development:

- **Breakthrough Starshot**[34]: A laser-driven sail concept aimed at reaching nearby star systems within decades;
- **Solar Cruiser** (NASA)[41]: A planned large-scale solar sail for heliophysics missions;
- **GeoSail**[16]: A proposed mission to study Earth's magnetotail using solar sail propulsion.

In parallel, ongoing research programs and international workshops (e.g., the International Symposium on Space Sailing series) have highlighted rapid progress in sail dynamics, attitude control methods, and mission design for high-performance trajectories, including fast interplanetary transfers and interstellar precursor missions [45].

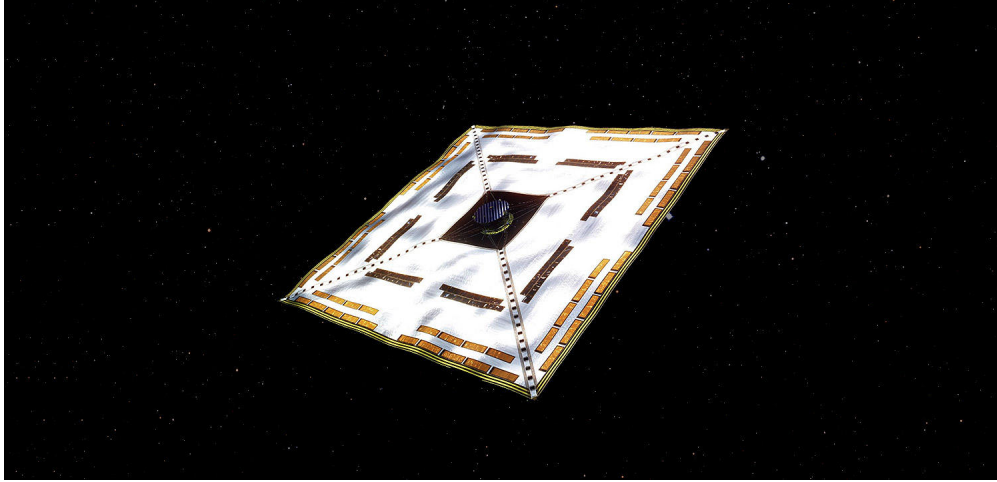


Figure 2.2: IKAROS (JAXA, 2010)

The working mechanism of a solar sail is based on the momentum transfer from photons. When photons, which are particles of light, strike a reflective surface, they transfer momentum to the sail, creating a force known as radiation pressure. This radiation pressure is extremely small, but in the vacuum of space, where there is no atmospheric drag, it can be used to gradually accelerate the spacecraft.

The force exerted on the sail can be described by the equation:

$$F = \frac{2PA}{c} \quad (2.2)$$

where:

- F is the force exerted by the radiation pressure,
- P is the power of the incident solar radiation,
- A is the area of the sail exposed to sunlight,
- c is the speed of light.

The factor of 2 is needed because the sail is assumed to be a perfect reflector, allowing for the maximum transfer of momentum. The orientation of the sail can be adjusted to change the direction of the force, which allows to maneuver in space. By tilting the sail relative to the incoming sunlight, the direction of the thrust can be modified, enabling changes in the spacecraft's trajectory or orbit.

2.1.2 Laser-Driven Sails

Laser-driven sails, also known as beam sails, are an advanced concept of photon propulsion in which thrust is generated by the momentum transfer of a high-power laser beam rather than by natural solar radiation. Although the underlying physical principle is identical to that of conventional solar sails, the use of an external coherent laser source enables significantly higher radiation pressure and potentially much greater spacecraft accelerations [34].

For a perfectly reflecting sail, the generated thrust is given by

$$F = \frac{2P_L A}{c}, \quad (2.3)$$

where P_L is the incident laser power, A is the illuminated sail area, and c is the speed of light.

A laser-driven sail system generally consists of an ultra-light reflective membrane, a high-power laser array, a beam-riding control system, and a lightweight spacecraft payload. Owing to the extremely high

power densities involved, the membrane must combine very low areal density with excellent optical reflectivity and thermal resistance.

The most well-known application of this concept is the *Breakthrough Starshot* initiative, which proposes accelerating gram-scale spacecraft to relativistic velocities using ground-based gigawatt-class laser arrays [34]. Although this technology remains at a conceptual stage, it has stimulated significant research into ultra-light membranes, beam-riding stability, and advanced deployable structures.

Despite its limited relevance to near-term space missions, laser-driven sailing further demonstrates the versatility of deployable membrane technologies and their potential for future high-performance space exploration.

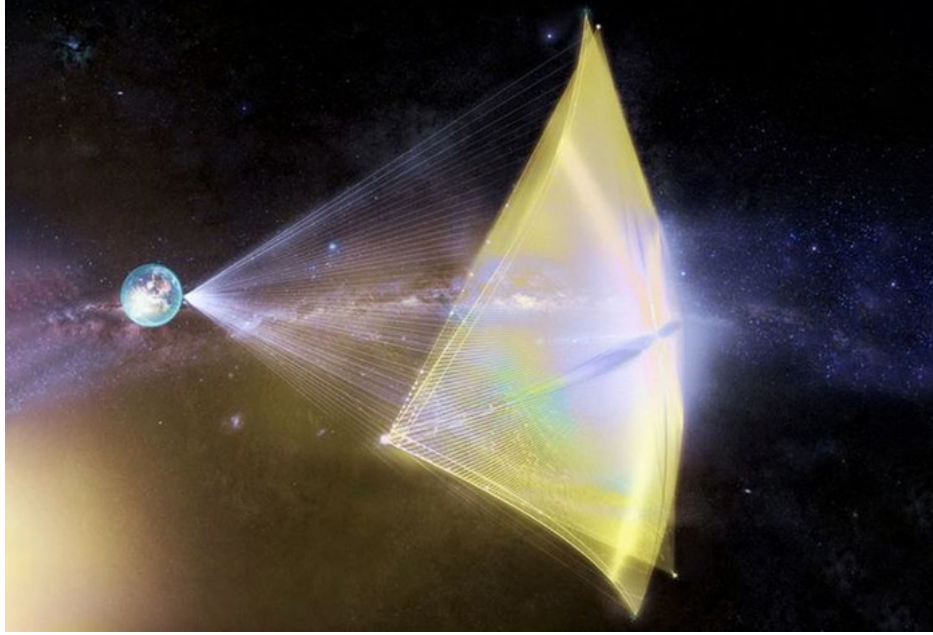


Figure 2.3: Conceptual representation of the Breakthrough Starshot laser-driven sail mission [34].

2.1.3 Drag Sails

Drag sails are deployable membrane structures designed to accelerate the orbital decay of spacecraft operating in Low Earth Orbit (LEO). Rather than generating propulsive forces, they exploit the residual atmospheric drag at low altitudes to reduce the orbital lifetime of satellites, providing a simple and passive solution for end-of-life disposal and space debris mitigation [22].

The aerodynamic drag force acting on a deployed sail can be approximated as

$$F_D = \frac{1}{2} \rho V^2 C_D A,$$

where ρ is the atmospheric density, V is the spacecraft velocity relative to the atmosphere, C_D is the drag coefficient, and A is the effective area exposed to the flow. By significantly increasing the projected area of the spacecraft, the drag sail enhances atmospheric braking, leading to a faster orbital re-entry.

The feasibility of this technology has been demonstrated through several in-orbit missions, including NASA's *NanoSail-D* and the *InflateSail* technology demonstrator, both of which successfully validated deployable membrane systems for passive deorbiting applications [22, 36].

Although drag sails are not intended for propulsion, they employ many of the same technologies as other membrane-based systems, including ultra-lightweight films, compact packaging, deployable support structures, and autonomous deployment mechanisms. Consequently, they have contributed significantly to the maturation of deployable membrane technologies and provide valuable engineering heritage for more advanced applications, such as Deployable Membrane Reflectors.

2.1.4 Electric Sails

Electric sails (E-sails) are an innovative propellantless propulsion concept that exploits the momentum transfer from the solar wind plasma rather than solar radiation pressure. Instead of using a large reflective membrane, an electric sail generates thrust through the electrostatic interaction between charged particles emitted by the Sun and a set of long, positively charged conductive tethers deployed from the spacecraft [20].

The propulsion mechanism relies on the Coulomb interaction between the charged tethers and solar wind ions. An onboard electron gun maintains the tethers at a high positive potential, causing incoming protons to be deflected by the electrostatic field. The resulting momentum exchange generates a continuous thrust whose magnitude depends on the local solar wind density and velocity rather than on the incident solar radiation.

A typical electric sail consists of a central spacecraft equipped with an electron gun and multiple conductive tethers deployed radially and maintained under tension through spacecraft rotation. Unlike conventional solar sails, no reflective membrane is required, although the system still relies on lightweight deployable structures capable of achieving very large effective interaction areas.

Electric sails offer several advantages, including continuous propellant-free propulsion, high specific impulse, and the potential for long-duration deep-space missions. However, their performance strongly depends on the highly variable characteristics of the solar wind, while the deployment and control of extremely long charged tethers remain significant technological challenges [49].

Although electric sails rely on a different physical principle than membrane-based sails, they share common engineering aspects such as deployable lightweight structures, compact launch configurations, and autonomous deployment systems. For this reason, their development has contributed to the broader advancement of large deployable space structures, although their technological relevance to Deployable Membrane Reflectors is more limited than that of conventional solar sails.

2.1.5 Magnetic Sails

Magnetic sails (M-sails) are a class of propellantless propulsion systems that generate thrust through the interaction between an artificial magnetic field and the charged particles of the solar wind. Unlike electric sails, which exploit electrostatic forces, magnetic sails rely on magnetohydrodynamic interactions to deflect solar wind plasma, thereby producing a reaction force on the spacecraft [2].

The propulsion system typically consists of a large superconducting loop or coil capable of generating an extended magnetic field around the spacecraft. As solar wind ions encounter the magnetic field, they are deflected by the Lorentz force, transferring momentum to the spacecraft. The resulting thrust depends on the magnetic field intensity, the effective interaction area, and the local properties of the solar wind plasma.

Compared with electric sails, magnetic sails have the potential to achieve larger effective interaction cross-sections without requiring extremely long conductive tethers. However, their practical implementation remains challenging due to the need for lightweight superconducting materials, cryogenic systems, and high-power electrical subsystems capable of sustaining the magnetic field in space [49].

Although magnetic sails do not employ deployable membranes, they share the common objective of achieving propellant-free propulsion through interaction with the space environment. Their development has contributed to the broader field of advanced sail technologies, demonstrating alternative approaches to continuous low-thrust propulsion, albeit with limited direct relevance to Deployable Membrane Reflectors.

2.1.6 Deployable Membrane Reflectors

Deployable Membrane Reflectors (DMRs) are ultra-lightweight space structures based on thin-film membranes that are compactly stowed during launch and deployed in orbit to form large functional surfaces. Thanks to their low areal density, high packaging efficiency, and scalability, DMRs have become enabling technologies for a wide range of space applications, including communication antennas, optical systems, thermal control devices, solar sails, and, more recently, Space-Based Solar Radiation Management (SB-SRM) concepts [9, 49].

Unlike conventional rigid structures, deployable membrane reflectors achieve large deployed dimensions while occupying only a fraction of the launch volume. This capability has stimulated extensive research

into lightweight materials, deployable support structures, and reliable deployment mechanisms, allowing membrane systems to reach dimensions that would be impractical using traditional spacecraft architectures.

Depending on the mission objectives, a DMR may perform different functions. Highly reflective membranes can be employed for photon propulsion in solar sails, while accurately shaped reflective surfaces are used for communication antennas and optical payloads. Large multilayer membranes have also been successfully adopted as thermal shields for scientific missions, demonstrating the versatility of deployable membrane technologies across multiple space applications [9].

Most Deployable Membrane Reflectors are manufactured using ultra-thin polymer films, such as Kapton or Mylar, coated with reflective metallic layers to improve their optical performance. Once deployed, the membrane must preserve its geometry under the combined effects of thermal loads, solar radiation pressure, and structural disturbances, making deployment reliability and shape stability two of the principal design requirements [49].

Over the past decades, the continuous evolution of membrane materials, deployable composite booms, inflatable structures, and autonomous deployment systems has considerably increased the technological maturity of DMRs. As a result, deployable membrane technologies have progressively evolved from relatively small communication reflectors to large multifunctional space structures capable of supporting increasingly ambitious missions.

Among the emerging applications of DMRs, Space-Based Solar Radiation Management has attracted growing interest because it exploits many of the technological capabilities originally developed for solar sails and deployable antennas. In these concepts, large reflective membranes are employed to partially redirect incoming solar radiation before it reaches the Earth, enabling distributed and scalable architectures that can be assembled using multiple spacecraft rather than a single monolithic structure.

Because Deployable Membrane Reflectors constitute the core technology investigated in this thesis, their historical evolution, mechanical architecture, membrane materials, deployment mechanisms, structural behaviour, and technology trade-offs are analysed in detail in Chapter 3.

2.1.7 Deployable Membrane Antennas

Deployable Membrane Antennas (DMAs) are among the most mature applications of deployable membrane technology. They consist of lightweight reflective membranes that are compactly stowed during launch and deployed in orbit to form large antenna apertures, enabling high-gain communication and remote sensing while significantly reducing launch mass and volume [9].

Unlike conventional rigid antennas, membrane antennas exploit deployable support structures to achieve reflector diameters well beyond the constraints imposed by launch vehicle fairings. Their large apertures make them particularly attractive for telecommunications, Earth observation, and radio astronomy missions, where antenna performance strongly depends on the available reflector area.

The gain of a deployable membrane antenna can be approximated by

$$G = \eta \left(\frac{\pi D}{\lambda} \right)^2,$$

where G is the antenna gain, η is the antenna efficiency, D is the reflector diameter, and λ is the operating wavelength. This relationship highlights the importance of large deployable reflectors in improving communication performance.

The development of membrane antennas has significantly advanced deployable space structures, contributing to the maturation of lightweight membranes, deployable booms, tensioning systems, and reflector shape control. These technologies constitute an important heritage for Deployable Membrane Reflectors, which adopt similar structural solutions while extending their applications beyond communications to optical systems, solar sailing, and Space-Based Solar Radiation Management [9].

2.1.8 Solar Power Sails

Solar Power Sails (SPS) represent an evolution of conventional solar sail technology by combining propellant-free propulsion with onboard electrical power generation. Unlike traditional solar sails, which rely exclusively

on Solar Radiation Pressure (SRP), SPS integrate thin-film photovoltaic cells within the membrane, allowing the spacecraft to simultaneously generate thrust and electrical power [49].

The propulsion mechanism remains identical to that of conventional solar sails, with solar photons transferring momentum to a highly reflective membrane. At the same time, part of the incident solar energy is converted into electrical power to supply the spacecraft bus, scientific payloads, communication systems, and, in some mission concepts, electric propulsion.

A typical Solar Power Sail consists of a deployable reflective membrane incorporating flexible photovoltaic cells, supported by lightweight deployable structures and connected to the spacecraft power management and attitude control systems. This multifunctional architecture improves mass efficiency by integrating propulsion and power generation into a single subsystem.

The most representative demonstration of this concept is JAXA's IKAROS mission, launched in 2010, which successfully validated both solar sail propulsion and the integration of thin-film photovoltaic devices within a deployable membrane [27]. Building upon this experience, the OKEANOS mission concept further extended the Solar Power Sail philosophy by combining solar radiation pressure with electric propulsion powered by the energy generated by the sail itself [38].

Compared with conventional solar sails, Solar Power Sails offer improved subsystem integration, onboard power generation, and greater mission flexibility, making them particularly attractive for long-duration deep-space exploration. More importantly, they demonstrate the evolution of deployable membranes from single-function propulsion devices to multifunctional spacecraft platforms. This design philosophy directly anticipates future Deployable Membrane Reflectors, where a single membrane may simultaneously perform structural, optical, thermal, and operational functions.

2.2 Comparative Assessment of Deployable Membrane Technologies

The technologies presented in this chapter demonstrate the remarkable versatility of deployable membrane systems in modern space engineering. Although originally developed to satisfy different mission objectives, ranging from propellant-free propulsion to telecommunications and spacecraft disposal, they all share a common technological foundation based on lightweight structures, compact packaging, and reliable deployment mechanisms.

From an engineering perspective, the principal challenge common to all deployable membrane systems is the realization of extremely large functional surfaces while maintaining low structural mass and high packaging efficiency. Achieving this objective requires the integration of advanced membrane materials, lightweight support structures, deployment mechanisms, and attitude control strategies capable of ensuring dimensional stability throughout the operational lifetime of the spacecraft.

Table 2.1 summarizes the principal characteristics of the deployable membrane technologies reviewed in this chapter.

Technology	Function	TRL	Deployable	Example of mission
Solar Sail	Propulsion	High	Yes	IKAROS
Laser Sail	Propulsion	Low	Yes	Starshot
Electric Sail	Propulsion	Med	Tethers	E-Sail
Magnetic Sail	Propulsion	Low	No	MPS
Drag Sail	Deorbiting	High	Yes	NanoSail-D
Solar Power Sail	Propulsion/Power	Med-High	Yes	OKEANOS
Membrane Antenna	Communications	High	Yes	IAE
DMR	Optical Systems	Med	Yes	JWST

Table 2.1: Comparison of the principal deployable membrane technologies.

A comparison of these technologies reveals several common design drivers that have guided the evolution of deployable membrane systems over the past decades. Independent of the specific mission application, the overall system performance is largely governed by the area-to-mass ratio, deployment reliability, membrane stability, and structural precision after deployment. These requirements have stimulated continuous

progress in membrane materials, deployable composite booms, folding techniques, inflatable structures, and autonomous deployment mechanisms.

Among the technologies reviewed, solar sails have provided the most significant contribution to the advancement of lightweight deployable structures through numerous successful in-orbit demonstrations. At the same time, deployable membrane antennas have established many of the structural and optical requirements associated with large reflective surfaces, while drag sails have demonstrated reliable deployment strategies for compact spacecraft platforms. Solar Power Sails have further extended this technological heritage by introducing multifunctional membrane architectures capable of simultaneously providing propulsion, structural support, and electrical power generation.

Deployable Membrane Reflectors can therefore be regarded as the convergence of these technological developments. Rather than representing an entirely new class of spacecraft, they combine the lightweight structural concepts developed for solar sails, the surface precision required by deployable antennas, the deployment reliability demonstrated by drag sails, and the multifunctional philosophy introduced by Solar Power Sails. This convergence makes DMRs particularly attractive for future large-scale space infrastructures requiring extremely large reflective surfaces with minimal structural mass.

The comparison presented in this chapter highlights that Deployable Membrane Reflectors currently represent one of the most promising applications of deployable membrane engineering. Their combination of scalability, modularity, packaging efficiency, and multifunctionality makes them suitable for emerging concepts such as distributed optical systems, large space observatories, and Space-Based Solar Radiation Management.

Building upon the technological background established in this chapter, the following chapter focuses exclusively on Deployable Membrane Reflectors. Their historical evolution, mechanical architecture, membrane materials, deployment mechanisms, structural behaviour, and technology trade-offs are analysed in detail in order to identify the most suitable configuration for the Space-Based Solar Radiation Management mission investigated in this thesis.

Deployable Membrane Reflectors: Architecture and Deployment Mechanisms

3.1 Introduction

In the previous chapter, an overview of the main deployable membrane technologies employed in space missions has been presented. Even if deployable membranes have been originally developed for different objectives, such as propulsion, telecommunications, spacecraft attitude and control and power generation, these structures have a common technology based on lightweight membranes, deployable structures, and compact packaging solutions.

In the last decades, Deployable Membrane Reflectors (DMRs) have emerged as one of the most promising technologies for future large-scale space infrastructures. The advantage of deploying extremely large reflective surfaces maintaining low structural mass and high packaging efficiency makes them suitable for many applications, from communication antennas to solar energy concentration and Space-Based Solar Radiation Management.

The DMR performance depends not only on the optical properties of the membrane but also on the structure that supports the configuration to be deployed.

One of the main aspects to be analyzed in this work is the deployment mechanism. In fact, Unlike conventional rigid spacecraft structures, DMRs must withstand the transition from a compact and stowed configuration to a stable deployed geometry while preserving dimensional accuracy under the combined effects of solar radiation pressure, thermal loads, structural vibrations, and external disturbances. Consequently, the design of these systems requires a trade off analysis of materials, deployable support structures, reliable deployment mechanisms, and membrane tensioning strategies in order to maintain structural stability in every phase mission.

Over the past decades, considerable progress has been obtained in the development of ultra-light polymer films, composite deployable booms, inflatable support structures and autonomous deployment mechanisms even if the realization of very large deployable reflectors still presents significant engineering challenges related to structural dynamics, deployment reliability, shape control, and scalability.

So the main objective of the current chapter is to make a review of the structural and mechanical aspects that characterize existing or concepts of Deployable Membrane Reflectors. With a general presentation of the structural architecture, the chapter investigates the principal subsystems of a typical DMR. Subsequently, the most widely adopted membrane materials, supporting structures, and deployment mechanisms are analyzed. At the end, the different technological solutions are compared with a trade off study providing the starting point of a baseline architecture adopted in the following chapters.

3.2 Deployable Membrane Reflectors architecture

Deployable Membrane Reflectors are lightweight structures composed by different systems and subsystems connected to each other and designed to provide large reflective surfaces with mass and volume limited by launch vehicles. Unlike conventional spacecraft rigid structures, DMRs are characterized by two different operative configurations: a compact stowed configuration during launch and a complete deployed configuration in orbit. The complex phase is the transition between these two configurations and it represents one of the most critical challenges related to DMRs missions[10].

Although the specific architecture varies according to the mission requirements and purpose, most DMRs share a common structural architecture, consisting of four primary systems:

- A reflective membrane;
- A support structure;
- A deployment mechanism;
- A spacecraft bus;
- Attitude control system.

These systems should be design to ensure a successful and a complete deployment and long-term functionality of the reflector[49].

In the figure 3.1, the architecture baseline of Lightsail[39] is presented where the main system related to a DMR spacecraft are identified.

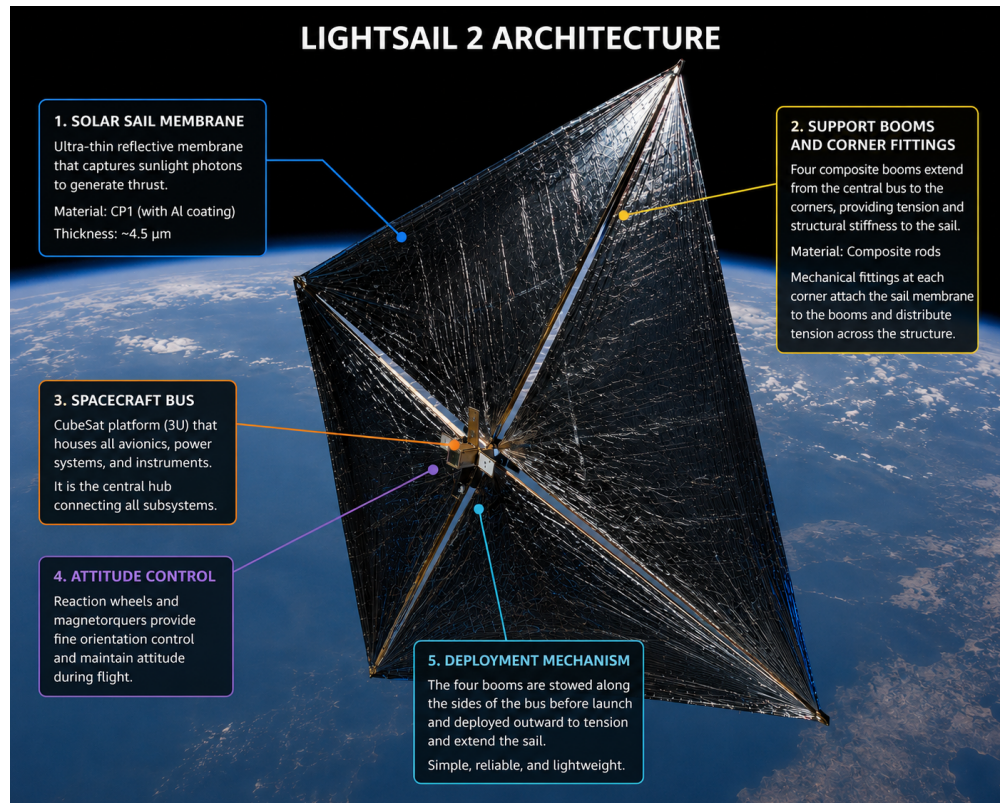


Figure 3.1: Lightsail spacecraft architecture with its principal systems

The membrane constitutes the primary functional element of the reflector. It provides the optical surface required for the mission and generally it is obtained from ultra-thin polymer films such as Kapton or Mylar and coated with metallic reflective layers. According to application field, the membrane can be optimized for solar reflectivity, for thermal or optical performance, making the selection of the material a fundamental aspect of the system design[10].

Different structure concepts have been proposed over the past decades, including deployable composite booms, inflatable supports, cable-supported architectures, and hybrid solutions. It must simultaneously guarantee high levels of stiffness, low mass, and compatibility with compact launch packaging[35].

The deployment subsystem enables the transition from the launch configuration to the operational geometry. This subsystem coordinates the release and unfolding of the membrane and the support structure.

Critical aspects are related to the deployment system, like incomplete deployment or excessive membrane wrinkling that can compromise the optical performance of the reflector[49].

The spacecraft bus constitutes the central element of the DMR architecture, providing the mechanical interface with the deployable reflector. Besides supporting all spacecraft subsystems such as avionics, electrical power subsystem, communication equipment, attitude and orbit control system (AOCS), and onboard computer, the bus manages the deployment sequence maintaining the stability in every operational phase.

Although each system has a distinct functional role, the overall performance of a Deployable Membrane Reflector depends strongly on the interaction between them. For example, the material and properties membrane directly influence the structural loads on the support structure. Similarly, the deployment mechanism causes the initial stress state of the membrane[9].

Purpose of the DMR spacecraft related to this study is the achievement of a high area-to-mass ratio while maintaining sufficient structural precision after deployment. In general when the reflector dimensions increase, the performance mission became more complex.

In the next sections, DMRs systems are described in the detail. Then the technologies and the material adopted in DMRs missions or concepts are presented and the result will be a trade-off analysis to select the best technology considering their interaction and the purpose of our case of study.

3.2.1 The Reflective Membrane

The reflective membrane is the primary functional element of a Deployable Membrane Reflector, providing a large-area surface required to accomplish the mission objectives. Depending on mission purpose, the membrane may reflect electromagnetic radiation, redirect solar flux, provide thermal shielding, or serve as the optical surface of the system. Consequently, its design directly influences the overall performance and stability of the entire spacecraft[49].

One of the great advantages of membrane reflectors is their exceptionally high area-to-mass ratio. By employing ultra-thin polymer films with thicknesses typically ranging from a few to several tens of micrometres, very large reflective surfaces can be achieved while maintaining an extremely low structural mass. This characteristic makes deployable membranes particularly attractive for missions requiring apertures or reflective surfaces that would be impractical using conventional rigid structures [10].

From a structural perspective, the membrane behaves as a flexible element that carries negligible bending stiffness and therefore relies almost entirely on tensile stresses to maintain its operational shape. For this reason, the membrane cannot operate as an independent structural component but requires an external support system capable of providing adequate tension and stability after deployment. The interaction between the membrane and the support structure represents one of the key aspects governing the entire life cycle of Deployable Membrane Reflectors[17].

In addition to its structural role, the membrane must satisfy several functional requirements imposed by the operational environment. During its lifetime, it is continuously exposed to solar radiation, thermal cycling, ultraviolet degradation, atomic oxygen in low Earth orbit, charged particles, and micrometeoroid impacts. Simultaneously, it must preserve its optical properties and dimensional stability despite these environmental loads. The identification of membrane materials represents a critical aspect of the reflector and it will be discussed in detail in Section 3.3.

The required optical properties depend strongly on the mission application. For communication antennas, the membrane must accurately preserve the reflector geometry to ensure efficient radio-frequency reflection. Optical systems require high surface precision, while solar sailing and Solar Radiation Management concepts demand high solar reflectivity combined with low areal density. Although these applications differ considerably, they all rely on the same fundamental capability of deployable membranes to provide extremely large, lightweight functional surfaces [49].

As reflector dimensions increase, maintaining membrane flatness becomes progressively more challenging. Wrinkling, local buckling, thermal distortions, and oscillation instability may significantly reduce the optical efficiency of the reflector. Consequently, the design of the reflective membrane cannot be analysed independently from the support structure, deployment strategy, and attitude control system.

3.2.2 Support Structure

The structure constitutes the load-bearing system of a Deployable Membrane Reflector. Its primary function is to provide the mechanical stiffness required to deploy, tension, and maintain the reflective membrane in its operational configuration throughout the mission. It is responsible for preserving the reflector geometry and ensuring the dimensional stability required to achieve the desired optical or reflective performance [17].

Unlike conventional spacecraft structures, which are designed to withstand structural loads through rigid components, the support system of a DMR must simultaneously satisfy two conflicting requirements:

- it must be sufficiently stiff to maintain the membrane shape after deployment;
- it must remain extremely lightweight and compatible with the limited volume during launch;
- the structure must ensure a reliable deployment sequence, avoiding interference with the membrane and limiting residual vibrations after deployment.

From literature in DMRs architectures the support consist of a central hub connected to a series of lightweight deployable members that extend radially after launch. These structural elements provide the mechanical interface between the spacecraft bus and the membrane, transferring tensile loads while minimizing structural deformation. Depending on the mission requirements and reflector dimensions, the supporting framework may also incorporate secondary tensioning elements, cable networks, or peripheral frames to improve membrane stability and shape accuracy[49].

Over the past three decades, significant progress has been achieved in the development of lightweight deployable structural concepts based on composite materials, inflatable members, and high stiffness deployable booms. These technological advances have enabled the realization of structures with unprecedented area-to-mass ratios while maintaining acceptable structural precision after deployment. Today, deployable structures represent one of the key enabling technologies for large membrane-based spacecraft.

Several configurations have been proposed in the literature and it will be described in the Section 3.4. Each structure is characterized by different levels of complexity, stiffness, deployment reliability, and scalability. It include solutions with articulated boom systems, coilable composite booms, inflatable supports, and hybrid architectures combining rigid and flexible structural elements.

3.2.3 Deployment Mechanisms

Another critical element of the design of a DMR is the deployment mechanism. It governs the transition from the compact launch (stowed configuration) to the fully operational reflector geometry (deployed configuration). Since the available volume inside the launch vehicle fairing is significantly smaller than the final deployed dimensions, the membrane and its supporting structure must be folded or packaged before launch and subsequently deployed in a controlled and reliable manner once the spacecraft reaches its operational orbit[10].

Deployment mechanism is dinamic,complex and one of the most critical aspect related to the successful of a mission.

The deployment process generally consists of three consecutive steps:

- the release of the stowed configuration;
- the extension of the support booms;
- the ultimately membrane tension.

Each phase must be carefully synchronized to ensure the correct geometry of the reflector and to prevent structural instabilities or incomplete deployment.

The deployment begins after spacecraft stabilization may rely on passive, active, or hybrid mechanisms depending on mission requirements. Passive systems exploit stored strain energy, springs, centrifugal forces, or inflatable elements to achieve deployment with minimal actuator complexity. Active systems employ electric motors, hinges, cables, or linear actuators to precisely control the deployment sequence. Hybrid

approaches combine the two strategies, using passive deployment for the primary structural expansion and active devices for membrane tension adjustment[17, 49].

Deployment mechanisms are critical due to high levels of failure and commonly they are designed with redundancy, simplified kinematic architectures, and extensive ground qualification campaigns to minimize the probability of failure.

In the last decades, numerous deployment concepts have been investigated for deployable membrane systems, including articulated boom deployment, inflatable structures, centrifugal deployment, cable-driven systems, and rigidizable architectures. Each solution offers different advantages in terms of mass, packaging efficiency, structural stiffness, deployment complexity, and scalability. As a result, the selection of the most appropriate deployment strategy strongly depends on the mission objectives and the required reflector dimensions.

A detailed trade off of the main deployment concepts adopted in deployable membrane structures is presented in Section 3.5, where the different architectures are analysed in terms of operating principle, technological maturity (TRL), structural performance, and suitability for large Deployable Membrane Reflectors spacecraft, objective of this thesis.

3.2.4 Spacecraft Bus and Control Subsystems

In a DMR every system (structure, membrane and deploying mechanism) are connected between them. The system that support their interaction is the spacecraft bus. This is the central support element, providing the mechanical, electrical, and functional interface between the deployable reflector and the spacecraft subsystems. While the membrane and its supporting structure represent the primary functional payload, the spacecraft bus is responsible for ensuring their deployment, operation, and long-term stability throughout the mission [21].

From a structural perspective, the spacecraft bus acts as the attachment point for the deployable reflector, supporting the folded membrane during launch and transmitting mechanical loads between the launch vehicle and the deployable architecture. Once the reflector has been deployed, the bus continues to provide the structural interface with the supporting booms and deployment mechanisms while maintaining the overall stability of the spacecraft.

Besides its structural role, the spacecraft bus accommodates all the conventional spacecraft subsystems required for mission operations. These typically include the Electrical Power Subsystem (EPS), the On-Board Computer (OBC), the Telemetry, Tracking and Command (TT&C) subsystem, the Attitude and Orbit Control System (AOCS), and the thermal control subsystem. These elements collaborate together to ensure the correct functioning of both the reflector and the spacecraft during all mission phases.

The spacecraft bus also supervises the deployment sequence through dedicated control electronics. Sensors distributed throughout the deployable structure monitor the extension of the supporting booms, membrane tension, locking devices, and deployment status, allowing onboard software to verify the successful completion of each deployment phase before initiating subsequent operations. This monitoring capability is essential because deployment is generally a one-time event that cannot be repeated once the spacecraft reaches orbit.

The increasing dimensions of modern deployable membrane systems have progressively strengthened the interaction between the spacecraft bus and the reflector itself. Rather than acting as an independent payload, the reflector influences the spacecraft inertia properties, disturbance torques, structural dynamics, and attitude control requirements. Consequently, the spacecraft and the deployable membrane must be designed as a single integrated system rather than as independent subsystems.

The general architecture described in this section establishes the foundation for the following sections, which investigate in greater detail the individual technologies enabling Deployable Membrane Reflectors, including membrane materials, supporting structures, deployment mechanisms, and their associated engineering trade-offs.

3.3 Membrane Materials

One of the main critical aspect of a reflective membrane is the selection of the material membrane.

The development of materials for space applications has been driven by the continuous demand for larger deployable surfaces combined with increasingly stringent mass limitations. Modern membrane films typically exhibit thicknesses ranging from 2 to 25 μm and are characterized by areal densities of only a few tens of grams per square metet. Despite their extremely low mass, these materials must withstand the severe environmental conditions encountered in space while preserving both their mechanical integrity and optical properties throughout the mission lifetime [49].

The principal requirements imposed on membrane materials are:

- extremely low areal density;
- high tensile strength and dimensional stability;
- resistance to thermal cycling;
- resistance to ultraviolet radiation and atomic oxygen;
- high reflectivity and low optical degradation;
- compatibility with compact folding and deployment.

These requirements are often in conflict. In fact, increasing membrane thickness generally improves mechanical robustness and decrease resistance but also increases structural mass, reducing the overall area-to-mass ratio of the reflector. Consequently, membrane selection is typically performed through a multidisciplinary trade-off balancing structural, thermal, optical, and manufacturing considerations.

Several polymeric materials have been proposed for deployable membrane applications over the past decades. Kapton, Mylar (PET), and CP1 have become the most widely adopted combininig low density, thermal stability, and mechanical performance. Their characteristics are discussed in the following subsections.

3.3.1 Polymeric Films

Most deployable membrane structures employ high-performance polymeric films as their structural substrate. These materials combine low density with excellent flexibility, allowing compact folding during launch while preserving sufficient mechanical strength after deployment.

Kapton®, a polyimide film developed by DuPont, has become one of the most extensively used materials for space membranes due to its exceptional thermal stability and resistance to ultraviolet radiation. It has been successfully employed in numerous missions, including the James Webb Space Telescope sunshield (see Fig. 3.2 and several deployable sail demonstrators[10].



Figure 3.2: A detail of James Webb Telescope membrane

Mylar® (polyethylene terephthalate, PET) represents another widely adopted membrane material. Compared with Kapton, Mylar generally exhibits higher optical quality and lower manufacturing cost, making it particularly attractive for solar sails and lightweight reflector applications. However, its thermal resistance is lower, limiting its suitability for missions involving prolonged exposure to elevated temperatures.

More recently, CP1 polyimide films have been developed to reduce moisture absorption while maintaining excellent dimensional stability. Compared with conventional Kapton, CP1 exhibits lower coefficients of thermal expansion and improved long-term stability, making it particularly attractive for precision optical systems and large deployable reflectors[49].

Although each material offers specific advantages, none simultaneously satisfies all structural, thermal, and optical requirements. Consequently, material selection depends strongly on the mission environment, reflector dimensions, deployment strategy, and expected operational lifetime.

3.3.2 Reflective Coatings

The polymer substrate alone does not provide the optical properties required for Deployable Membrane Reflectors. For this reason, thin metallic coatings are deposited on the membrane surface to increase solar or electromagnetic reflectivity while preserving the flexibility of the underlying film.

Aluminium coating is by far the most commonly adopted material owing to its high solar reflectance, low density, and relatively simple deposition process. Alternative coatings based on silver or gold may be employed for specific optical although their higher cost generally limits their use.

Besides improving reflectivity, metallic coatings also contribute to thermal management by controlling the membrane absorptivity and emissivity. These optical properties directly influence the equilibrium tem-

perature of the reflector and therefore affect thermal deformation and dimensional stability during operation.

The deposition process must guarantee uniform coating thickness while maintaining excellent adhesion to the polymer substrate. Typical coating thicknesses range from a few tens to several hundreds of nanometres, contributing negligibly to the overall structural mass while significantly improving the optical performance of the reflector [10].

3.3.3 Comparison of Membrane Materials

In Table 3.1 the principal characteristics of each type of membrane materials most commonly employed in deployable space structures are presented.

Name Material	Density	Thermal Stability	Optical Stability	Typical Applications
Kapton®	High	Excellent	High	JWST, Solar Sails
Mylar®	Medium	Good	Excellent	Solar Sails, Reflectors
CP1	Medium	Excellent	Excellent	Precision Reflectors

Table 3.1: Comparison of typical membrane materials for Deployable Membrane Reflectors.

Among these materials, Kapton remains the current industrial reference with high technological maturity level and extensive flight heritage. Nevertheless, CP1 is increasingly attracting interest for future large Deployable Membrane Reflectors because of its improved thermo-mechanical stability and reduced moisture absorption. The final material selection ultimately depends on the mission requirements and will therefore be reconsidered during the technology trade-off presented in the next paragraphs of this works.

3.4 Support Structure

As we said in the previous sections, the support structure is one of the key enabling technologies of Deployable Membrane Reflectors (DMRs), providing the mechanical framework required to deploy, tension, and maintain the membrane in its operational configuration. The structural architecture is responsible for preserving the reflector geometry while withstanding both internal and external loads throughout the mission lifetime[17].

The design of support structure is governed by a series of demanding and often conflicting requirements. The structure must:

- provide high levels of stiffness in order to minimize membrane deformation and maintain the required optical accuracy;
- remain lightweight;
- highly compact when stowed;
- capable of reliable deployment in the space environment.

In this way, the trade off analysis related to the support structure is commonly evaluated through the achievable deployed area-to-mass ratio and the packaging efficiency of the deployment architecture.

During operation, the supporting structure is subjected to several disturbance sources, including thermal gradients, solar radiation pressure, spacecraft manoeuvres, and residual dynamic effects generated during deployment. These disturbances may induce elastic deformation, local buckling, or low-frequency vibrations that degrade the performance of the reflector. Therefore, structural stiffness and dynamic stability become increasingly important as the reflector dimensions increase.

Over the past decades, numerous structural concepts have been proposed for DMRs spacecraft. Early architectures relied primarily on articulated metallic frameworks similar to conventional deployable antennas. Subsequent developments in material technology introduced lightweight composite booms, inflatable structures, and hybrid configurations capable of achieving significantly higher area-to-mass ratios while improving packaging efficiency and deployment reliability. These technological advances have enabled membrane reflectors to evolve from relatively small communication antennas to large-scale deployable structures for scientific missions and emerging Space-Based Solar Radiation Management concepts[4].

Although each structural concept employs different deployment strategies and mechanical solutions, the purpose of all architectures is providing a stable and lightweight support capable of preserving membrane geometry after deployment. The following subsections review the state of the art of support structures highlighting their operating principles, advantages and limitations, and technological maturity to realize a comparison between them.

3.4.1 Articulated Boom Structures

Articulated boom structures represent one of the earliest structural solutions developed for deployable space systems. Their operating principle is based from conventional space structure on rigid structural elements connected through mechanical joints or hinges, allowing the entire framework to be folded into a compact configuration during launch and subsequently unfolded once in orbit. These architectures were originally developed for deployable antennas and solar array support structures, where structural stiffness and deployment reliability were considered the primary design drivers[9, 17].

Unlike modern flexible boom concepts, articulated structures rely on discrete rigid elements rather than elastic deformation. During deployment, each boom rotates about one or more hinge mechanisms until reaching its final locked configuration, where dedicated latching devices provide the structural continuity required for operational loads. This approach offers relatively high structural stiffness after deployment and well-controlled kinematics, making articulated systems particularly attractive for medium-sized deployable structures.

A typical articulated boom system (see Fig.3.3) consists of a central hub connected to multiple rigid segments through revolute joints. Deployment is generally achieved using torsion springs, electric motors, or cable-driven mechanisms, while mechanical locks ensure complete structural stiffness once the final configuration has been reached. The reflective membrane is subsequently tensioned between the deployed booms, allowing the required optical or reflective surface to be established.

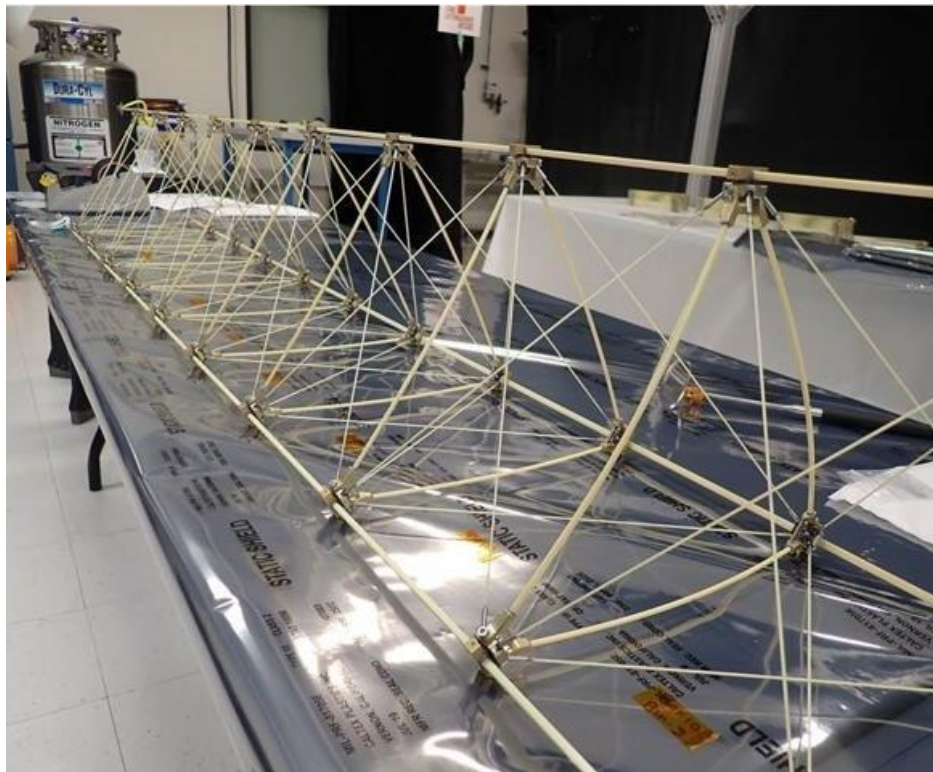


Figure 3.3: Articulated boom structure from NASA Deployable Mast mission.. Rigid segments connected by mechanical hinges unfold after launch to provide a stiff supporting framework for lightweight membranes or reflector surfaces

The principal advantage of articulated boom structures lies in their mechanical simplicity and high structural rigidity after deployment. Since the supporting members are manufactured as rigid components, their elastic deformation is generally limited, resulting in relatively good dimensional accuracy and predictable structural behaviour. Furthermore, the deployment sequence can be accurately controlled using conventional mechanical actuators with a high TRL, reducing the uncertainty associated with membrane deployment.

Despite these advantages, articulated boom systems also present several limitations that restrict their applicability to very large deployable reflectors. The large number of hinges, locking devices, and mechanical interfaces increases both the structural mass and the overall system complexity. Technically every element of framework could introduce potential failure modes, increasing the risk of incomplete deployment or mechanical malfunction and if the reflector dimensions increase, these disadvantages become progressively more significant.

Another important limitation is the packaging efficiency. Because articulated booms are composed of discrete rigid segments, their stowed configuration generally occupies a larger volume than continuous deployable booms. Consequently, these systems become less attractive for missions requiring reflector diameters of several tens of metres, where launch volume constitutes one of the primary design target.

For this reasons in the last decades, articulated boom structure has been replaced by innovative lightweight composite booms capable of achieving higher deployment ratios and significantly lower structural mass. Nevertheless, articulated architectures continue to be employed for missions such as deployable antennas, solar arrays, and medium-scale membrane reflectors.

3.4.2 Coilable Booms: STEM and Bi-STEM

The need for increasingly larger deployable membrane structures led to the development of flexible deployable booms capable of achieving significantly higher deployment ratios than conventional articulated structures. Among the earliest and most successful solutions are the Storable Tubular Extendible Member (STEM) and its subsequent evolution, the Bi-STEM configuration. These technologies have played a fundamental role in the development of deployable antennas, solar arrays, membrane reflectors, and lightweight space structures, providing the technological foundation for many modern deployable boom architectures[29].

A STEM boom is manufactured from a thin metallic strip that is permanently curved into a tubular cross-section. During launch, the boom is elastically flattened and wound around a storage drum, allowing long structural members to be packaged within a very compact volume. Once released, the stored elastic strain energy causes the boom to recover its original tubular geometry while simultaneously extending from the deployment mechanism.

This self-deployment capability represents one of the principal advantages of STEM technology, as it considerably reduces the number of motors, hinges, and actuators required during deployment. Furthermore, the continuous nature of the boom eliminates many of the mechanical joints present in articulated structures, improving packaging efficiency and reducing the number of potential failure points.

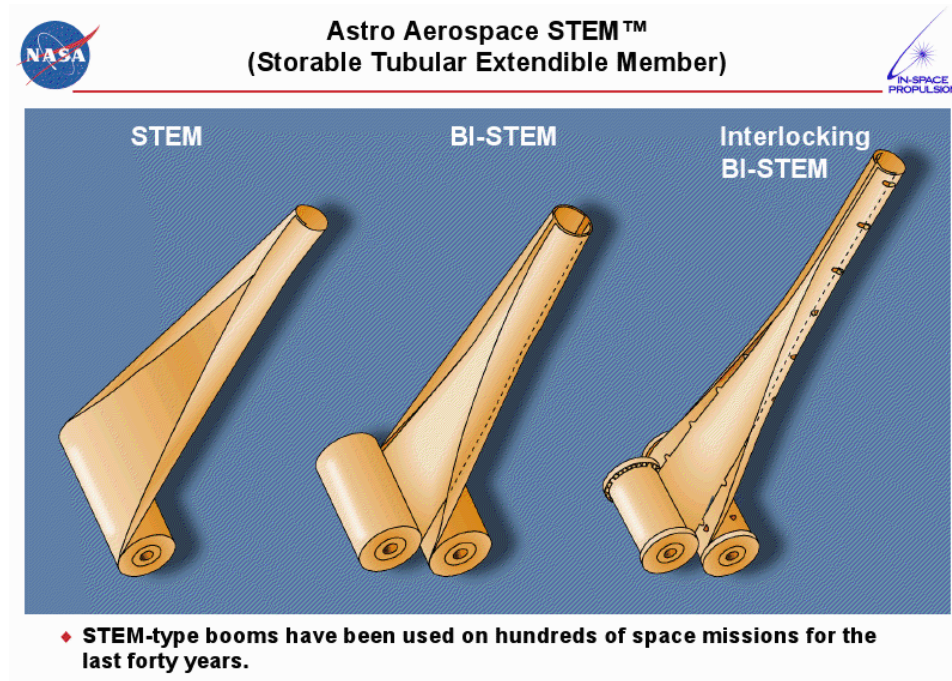


Figure 3.4: Operating principle of a Storable Tubular Extendible Member (STEM) and Bi-STEM. The metallic strip is flattened and coiled during launch before elastically recovering its tubular shape during deployment. Credits to @NASA.

Despite these advantages, conventional STEM booms exhibit relatively limited torsional stiffness and are susceptible to local buckling when subjected to bending or compressive loads. These limitations become increasingly significant as boom length increases, reducing the suitability of single STEM architectures for very large deployable membrane systems.

To overcome these limits, the Bi-STEM configuration was developed by coupling two STEM elements back-to-back. The resulting closed cross-section significantly increases the flexural and torsional stiffness while preserving the compact packaging characteristics of the original concept. Compared with a single STEM boom, Bi-STEM structures exhibit improved load-carrying capability, greater dimensional stability, and enhanced deployment reliability, making them suitable for larger deployable spacecraft structures.

The mechanical behaviour of coilable booms is governed primarily by elastic strain energy stored during packaging. Consequently, deployment occurs without the need for continuous actuation, although damping devices or controlled release mechanisms are often incorporated to regulate the deployment speed and prevent excessive dynamic oscillations. Once fully deployed, locking devices or dedicated tensioning systems may be employed to improve structural stability depending on the mission requirements.

Coilable booms have been successfully employed in numerous deployable spacecraft system such as NanoSail-D and Lightsail missions owing to their excellent packaging efficiency and relatively simple deployment mechanism.

The experience gained through the development of STEM and Bi-STEM technologies directly influenced the design of more advanced composite deployable booms. In particular, the Tape-Rolled Adaptive Composite (TRAC) boom adopts many of the deployment principles established by coilable booms while significantly improving structural stiffness, deployment reliability, and scalability through the use of composite materials. For this reason, TRAC booms are now the most promising structural solutions for future large Deployable Membrane Reflectors.

3.4.3 TRAC Booms

Developed by NASA Langley Research Center for applications requiring large deployable surfaces, The Tape-Rolled Adaptive Composite (TRAC) booms combine lightweight composite materials with an innovative

collapsible cross-section, achieving an excellent compromise between structural stiffness, packaging efficiency, and deployment reliability. Their successful implementation in the Advanced Composite Solar Sail System (ACS3)[40] mission has demonstrated the maturity of this technology for future large deployable spacecraft.

The operating principle of a TRAC boom is based on the elastic deformation of a thin composite shell. In the stowed configuration, the boom is flattened and rolled around a deployment spool, occupying a very limited volume. During deployment, the stored elastic strain energy allows the boom to progressively recover its original geometry while extending from the spacecraft without requiring complex articulated joints. This self-deployment capability considerably simplifies the mechanical architecture and reduces the number of potential failure points compared with traditional articulated structures.

A distinctive characteristic of TRAC booms is their triangular closed cross-section obtained by joining two curved composite laminates. Unlike open-section tape-spring booms, this geometry provides significantly higher bending and torsional stiffness while preserving the excellent packaging efficiency typical of rollable structures. The increased structural rigidity is particularly advantageous for large Deployable Membrane Reflectors, where membrane flatness and dimensional stability strongly depend on the stiffness of the supporting framework.

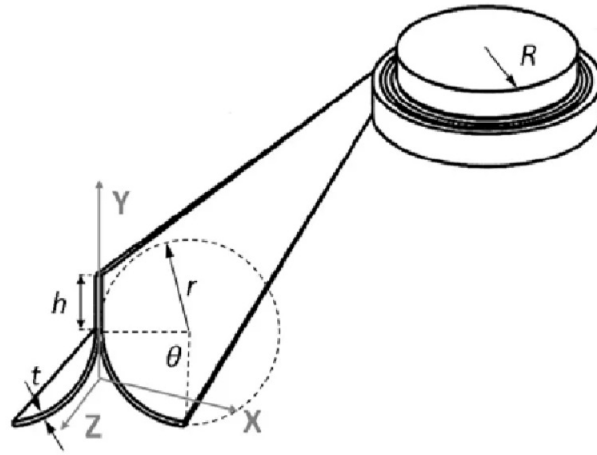


Figure 3.5: Schematic of TRAC boom section architecture from[31].

Composite materials also provide several advantages over conventional metallic booms. Carbon-fibre reinforced polymer (CFRP) laminates offer high specific stiffness, excellent fatigue resistance, and reduced thermal expansion, allowing the reflector geometry to remain more stable under the large temperature variations experienced in space. Furthermore, composite manufacturing techniques enable the tailoring of laminate properties according to the specific structural requirements of the mission, optimizing both mass and mechanical performance [29].

From a systems engineering perspective, TRAC booms satisfy many of the key requirements imposed on modern deployable membrane structures. They provide high deployment ratios, low structural mass, compact packaging, and excellent scalability, making them suitable for reflectors ranging from a few metres to several tens of metres in diameter. Their continuous geometry also reduces the number of mechanical interfaces, improving deployment reliability and simplifying the integration with the membrane tensioning system.

The most significant demonstration of this technology is NASA's Advanced Composite Solar Sail System (ACS3), launched in 2024. The mission successfully deployed four approximately 7-m-long composite TRAC booms supporting an 80 m² solar sail, validating both the deployment mechanism and the structural behaviour of composite rollable booms in orbit. The results confirmed the capability of TRAC technology to provide lightweight and reliable support for large membrane structures, representing a major milestone in the maturation of deployable composite architectures [40].

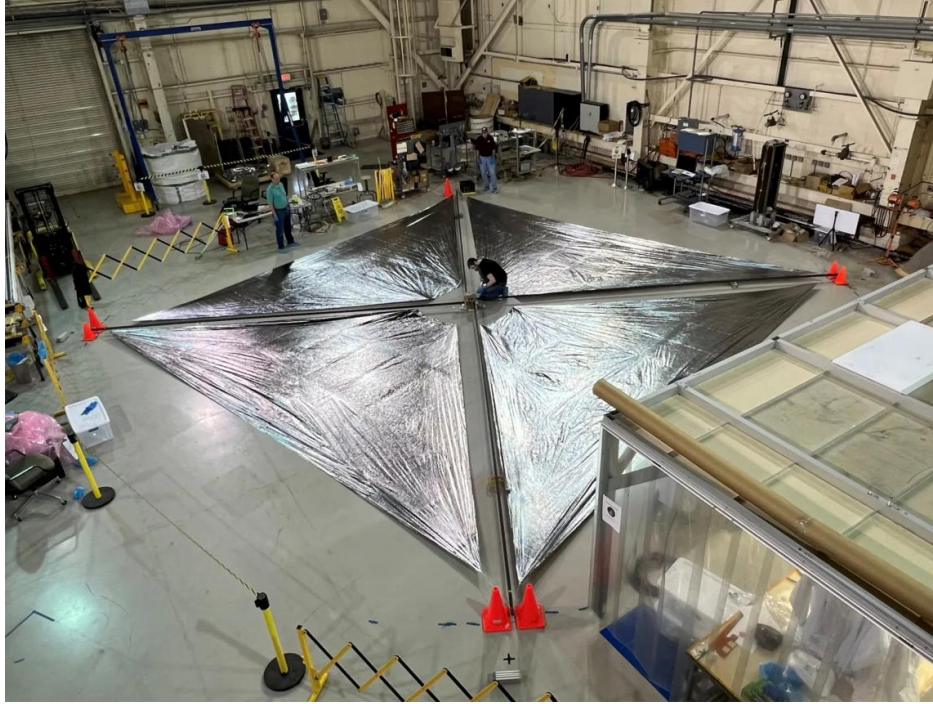


Figure 3.6: Concept of a Tape-Rolled Adaptive Composite (TRAC) boom showing the transition from the flattened stowed configuration to the deployed triangular cross-section adapted from [40].

Despite these advantages, several engineering challenges remain. As the boom length increases, local buckling, manufacturing tolerances, deployment dynamics, and thermoelastic deformations become increasingly significant. In addition, ensuring synchronization among multiple booms during deployment requires accurate control strategies and careful structural integration with the membrane. These aspects remain active research topics for future large-scale Deployable Membrane Reflectors.

Owing to their high structural efficiency, excellent packaging capability, and demonstrated flight heritage, TRAC booms are currently considered one of the most suitable supporting structures for large deployable membrane systems. Consequently, they will be adopted as one of the reference technologies in the trade-off analysis presented in Section 3.7.

3.4.4 Inflatable Structures

Inflatable structures represent an alternative solution to support large deployable membranes, relying on pneumatic inflation rather than mechanical unfolding to achieve the operational configuration. Since their introduction in the 1960s, inflatable technologies have attracted considerable interest due to their exceptional packaging efficiency and their ability to deploy very large structures from extremely compact launch volumes. Applications include communication antennas, solar concentrators, drag sails, large reflectors, and inflatable habitats[4].

The operating principle is based on the inflation of thin-walled tubular members using a stored gas. During launch, the inflatable elements are folded together with the membrane into a compact configuration. Once in orbit, a pressurized gas is released into the inflatable tubes, causing them to expand and assume their designed geometry. The inflated members then provide the structural support required to tension and stabilize the membrane.

Depending on the mission requirements, inflatable structures may remain continuously pressurized throughout the operational lifetime or undergo a rigidization process after deployment[12].

One of the principal advantages of inflatable structures is their extremely high packaging efficiency. In addition, inflatable systems generally require fewer moving mechanical parts than articulated or boom-based architectures reducing mechanical complexity during deployment phase.

Despite these advantages, inflatable structures also present several engineering challenges. Maintaining dimensional accuracy after deployment is more difficult than in rigid or composite boom systems because the supporting members exhibit relatively low bending stiffness and are more sensitive to thermal distortions and dynamic excitations. Then long-term structural integrity depends on the reliability of the inflation system and, for non-rigidized concepts, on the ability to maintain internal pressure over the entire mission duration.

Several experimental missions have demonstrated the feasibility of inflatable space structures. NASA's Inflatable Antenna Experiment (IAE) (see Fig.3.7) successfully validated the deployment of a large inflatable reflector, while the European InflateSail mission demonstrated inflatable boom technology for deployable membrane systems. These missions significantly increased the Technology Readiness Level (TRL) of inflatable architectures and provided valuable experience in deployment dynamics and membrane integration [36].

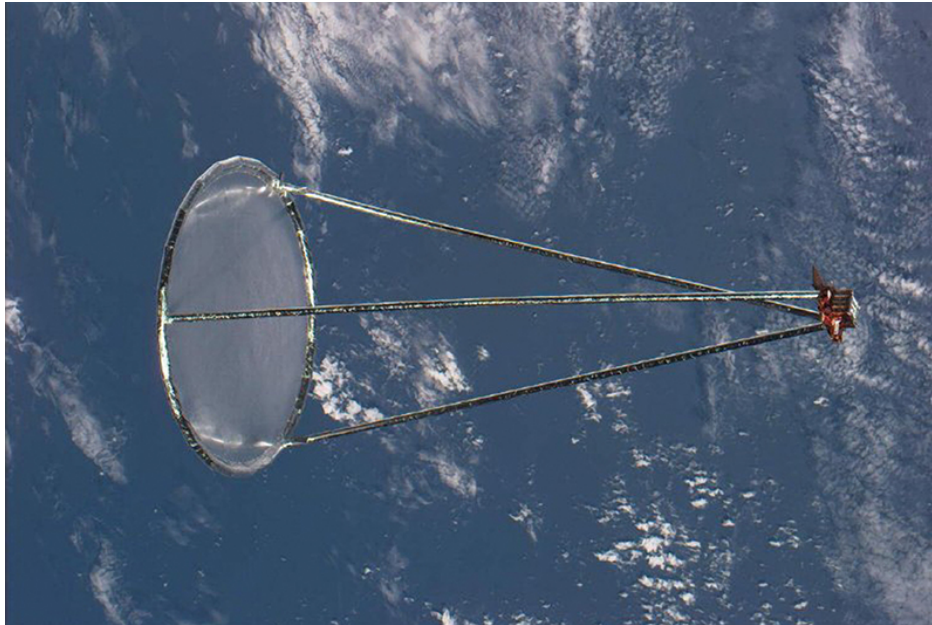


Figure 3.7: Architecture of NASA Inflatable Antenna Experiment[4]

Although inflatable structures offer unmatched packaging efficiency, their relatively low structural stiffness and sensitivity to environmental disturbances currently limit their application in missions requiring high optical precision. Consequently, they are generally considered more suitable for large communication reflectors, drag devices, and low-precision membrane systems than for high-accuracy Deployable Membrane Reflectors intended for optical properties or Solar Radiation Management applications.

3.4.5 Cable-Supported Structures

Cable-supported structures represent one of the most effective solutions for achieving large deployable reflector surfaces while minimizing structural mass. Rather than relying solely on rigid supporting members, these architectures employ a network of pretensioned cables to distribute loads and maintain the desired membrane geometry. This approach has been extensively adopted for large deployable antennas and mesh reflectors, where maintaining an accurate surface profile is essential for mission performance [9].

The fundamental principle of cable-supported structures is the stabilization of the reflector through tensile equilibrium. Following deployment, a network of radial and circumferential cables is tensioned between the central hub and the peripheral structural elements. The membrane or reflective mesh is attached to this network, allowing tensile forces to maintain the required surface geometry while minimizing the amount of structural material.

Compared with rigid frame architectures, cable-supported systems offer several advantages. Since cables efficiently transmit tensile loads while carrying negligible bending moments, they provide an excellent

strength-to-mass ratio and allow the realization of very large deployable apertures with relatively low structural mass. In addition, the flexibility of the cable network facilitates compact packaging during launch and simplifies the deployment sequence.

One of the most representative examples of this technology is the AstroMesh deployable reflector developed by Northrop Grumman. The AstroMesh architecture consists of a deployable perimeter truss supporting a pretensioned cable network, on which a metallic reflective mesh is mounted. Since its introduction, this concept has been successfully employed on numerous communication satellites and is considered one of the most mature deployable reflector technologies currently available [7].



Figure 3.8: Typical cable-supported reflector architecture based on the AstroMesh concept. A deployable perimeter structure supports a pretensioned cable network that maintains the reflective surface geometry. @Credits from [7].

Despite their excellent structural efficiency, cable-supported architectures also present important engineering challenges. The reflector geometry depends strongly on the distribution of cable tension, making manufacturing tolerances and deployment accuracy critical factors. Small variations in cable length or pretension may introduce surface distortions that degrade optical or radio-frequency performance. Furthermore, the dynamic interaction between the membrane, cables, and supporting frame can generate low-frequency vibration modes that require careful structural analysis.

Although cable-supported architectures have primarily been developed for deployable communication antennas, their lightweight and flexible design and excellent scalability have also inspired several concepts for future Deployable Membrane Reflectors.

3.4.6 Preliminary Trade Off Analysis of Support Structures

The support structures presented in the previous sections represent the principal technological solutions currently adopted for Deployable Membrane Reflectors (DMRs). Although all these architectures pursue the same objective of supporting and tensioning a lightweight membrane after deployment, they differ significantly in terms of structural behaviour, packaging efficiency, deployment complexity, scalability, and technological maturity.

Articulated boom structures provide excellent structural rigidity and predictable deployment kinematics owing to their rigid members and mechanical joints. However, their relatively high mass, large number of moving components, and limited packaging efficiency reduce their suitability for very large membrane reflectors.

STEM and Bi-STEM booms represented a major advancement over articulated systems by introducing continuous deployable members capable of self-deployment through stored elastic strain energy. Their

compact packaging and relatively simple deployment mechanism have enabled numerous deployable space structures. Nevertheless, their limited torsional stiffness and susceptibility to local buckling reduce their applicability for very large membrane reflectors requiring high dimensional stability.

Among the currently available technologies, TRAC booms provide one of the best compromises between lightweight construction, structural stiffness, packaging efficiency, and deployment reliability. Their composite triangular cross-section considerably improves both bending and torsional stiffness while maintaining the compact stowage characteristics typical of rollable structures.

Inflatable structures offer the highest packaging efficiency and can deploy extremely large structures from very compact launch volumes. However, their relatively low structural stiffness and dependence on inflation or rigidization processes make them less attractive for complex applications like space sunshields.

Cable-supported structures constitute one of the most mature technologies for large deployable antennas. Their excellent area-to-mass ratio and scalability have been demonstrated in several communication satellites employing AstroMesh reflectors. However, their structural behaviour strongly depends on cable pretension and deployment accuracy, making them more challenging for precision membrane reflectors.

To provide a preliminary engineering assessment, the different structural architectures have been compared using a weighted trade-off based on the principal design requirements of the proposed Space-Based Solar Radiation Management mission. Six evaluation criteria were considered: structural mass, bending stiffness, packaging efficiency, deployment reliability, scalability, and technological maturity (TRL). The weighting factors adopted for the analysis are reported in Table 3.2.

Criterion	Weight
Structural Mass	0.20
Structural Stiffness	0.20
Packaging Efficiency	0.15
Deployment Reliability	0.20
Scalability	0.15
Flight Heritage / TRL	0.10

Table 3.2: Weighting factors adopted for the preliminary structural trade-off.

A score is given for each structure on a five-point scale, where 1 indicates poor performance and 5 represents excellent performance with respect to each criterion. The resulting weighted scores are summarized in Table 3.3.

Architecture	Mass	Stiff.	Pack.	Reliab.	Scale	TRL	Score
Articulated Boom	2	5	2	4	2	5	3.25
STEM / Bi-STEM	4	3	5	4	3	4	3.80
TRAC Boom	5	5	5	4	5	4	4.75
Inflatable	5	2	5	3	5	3	3.95
Cable-Supported	4	4	3	4	5	5	4.10

Table 3.3: Preliminary trade-off of supporting structures for Deployable Membrane Reflectors.

In addition to the engineering assessment, each structural concept can be associated with representative flight missions that demonstrate its maturity and operational heritage, as summarized in Table 3.4.

Architecture	Representative Mission	Status
Articulated Boom	Large deployable antennas[3]	Operational
STEM / Bi-STEM	Mars Express (MARSIS boom)[15]	Operational
TRAC Boom	NASA ACS3[40]	Flight Demonstration
Inflatable	Inflatable Antenna Experiment[4]	Demonstrated
Cable-Supported	AstroMesh Reflector[7]	Operational

Table 3.4: Representative missions for the principal supporting structures.

The preliminary analysis identifies TRAC boom as the best solution as starting point for this work. Its combination of low structural mass, high stiffness, excellent packaging efficiency, and recent in-orbit validation

provides the highest overall score among the technologies considered. Among the Cable-supported architectures, they also exhibit excellent structural performance and flight heritage, particularly for communication reflectors, while inflatable structures remain attractive for applications where packaging efficiency, stiffness and reliability are the dominant design drivers.

It should be clear that the final trade off to select the best DMR architecture to study considers not only the supporting structure. The final selection of the baseline Deployable Membrane Reflector architecture also depends on membrane materials, deployment mechanisms, structural dynamics, and system-level integration. These aspects will be investigated through the comprehensive technology trade-off presented in Section 3.6.

3.5 Structural stability of Deployable Membrane Reflectors

The successful of a Deployable Membrane Reflector (DMR) spacecraft depends not only on the selection of materials, support structures, and deployment mechanisms, but also on the structural stability of the system once deployed. Unlike conventional spacecraft structures, deployable membrane reflectors are characterized by extremely low stiffness, large flexible surfaces, and high area-to-mass ratios. These characteristics make them particularly sensitive to environmental disturbances and geometric imperfections, requiring careful structural analysis during the design phase [31].

Following deployment, the membrane and its supporting structure behave as an integrated flexible system whose response is governed by the interaction between membrane tension, boom stiffness, thermal loads, and spacecraft dynamics. Small deformations of the supports may produce significant variations in membrane geometry, directly affecting the optical or reflective performance of the system. Consequently, structural behaviour becomes one of the principal design drivers for large deployable membrane reflectors.

In general, membrane structures cannot sustain compressive stresses. Instead, they rely almost entirely on tensile loading to maintain their operational shape. Any reduction in membrane tension may result in local wrinkling, slack regions, or dynamic oscillations, degrading both structural stability and mission performance. Maintaining an appropriate tension distribution therefore represents one of the primary objectives of the supporting structure and deployment system.

The following sections discuss the principal phenomena governing the behaviour of deployable membrane structures, including membrane tensioning, wrinkling, thermoelastic effects, and structural dynamics.

This is essential for selecting an appropriate reflector architecture.

3.5.1 Membrane Tensioning

Membrane tensioning is one of the fundamental aspects governing the structural behaviour of Deployable Membrane Reflectors (DMRs). Unlike conventional rigid structures, thin-film membranes possess negligible bending stiffness and are therefore unable to sustain compressive loads. Their structural integrity relies almost entirely on tensile stresses generated during deployment and maintained throughout the operational lifetime of the spacecraft. An appropriate tension distribution is essential to preserve the desired reflector geometry, prevent structural instabilities, and guarantee the optical or reflective performance required by the mission [9, 31].

Following deployment phase, the membrane is unfolded by the supporting structure through the action of deployable booms, cable networks, inflatable members, or centrifugal forces, depending on the selected architecture. The main objective of the tensioning system is to establish a nearly uniform tensile stress field over the membrane surface while minimizing local stress concentrations that could lead to excessive deformation or material failure.

Considering an ideal isotropic membrane subjected to uniform biaxial loading, the membrane stress can be approximated by the equation:

$$\sigma = \frac{T}{t} \quad (3.1)$$

where σ is the membrane stress, T is the in-plane tensile load per unit width, and t is the membrane thickness.

This simple formula describes one of the principal design challenges associated with DMR systems. Since the membrane thickness is typically only a few micrometres, relatively small tensile loads generate significant

stress levels. Consequently, the membrane must be tensioned sufficiently to maintain its geometry while avoiding excessive stresses that could initiate tearing or accelerate material degradation.

The distribution of membrane tension depends strongly on both the supporting structure and the deployment sequence. Geometric imperfections, manufacturing tolerances, asymmetric deployment, and non-uniform thermal expansion may produce localized stress concentrations, resulting in non-uniform deformation of the reflective surface. These effects become increasingly important as the reflector dimensions increase and are therefore carefully considered during the structural design of large membrane systems.

Because membrane tension directly influences almost every aspect of the structural response, it represents the foundation upon which the remaining structural phenomena are built. In particular, insufficient or non-uniform tension is the primary cause of membrane wrinkling, which is discussed in the following section.

3.5.2 Wrinkling Phenomena

Wrinkling is one of the most critical structural phenomena affecting Deployable Membrane Reflectors (DMRs). Owing to their extremely small thickness and negligible bending stiffness, thin-film membranes are unable to sustain compressive stresses. Whenever compressive loads develop locally, the membrane relieves these stresses by forming out-of-plane deformations, commonly referred to as wrinkles. Although wrinkling prevents structural collapse, it alters the membrane geometry and may significantly degrade the optical, thermal, or reflective performance of the system [9].

Wrinkles may originate from several sources during mission lifetime. The most common causes are:

- non-uniform membrane pretension;
- deployment imperfections;
- thermal gradients;
- spacecraft manoeuvres;
- external sources such as Solar Radiation Pressure.

From a mechanical point of view, membrane behaviour is governed by the inability to carry compressive stresses. As soon as one of the in-plane principal stresses becomes negative, the membrane locally buckles until the compressive stress is almost completely released. Consequently, the structural response differs significantly from that of conventional plates or shells, requiring dedicated analytical formulations such as Tension Field Theory and geometrically nonlinear finite element models[31].

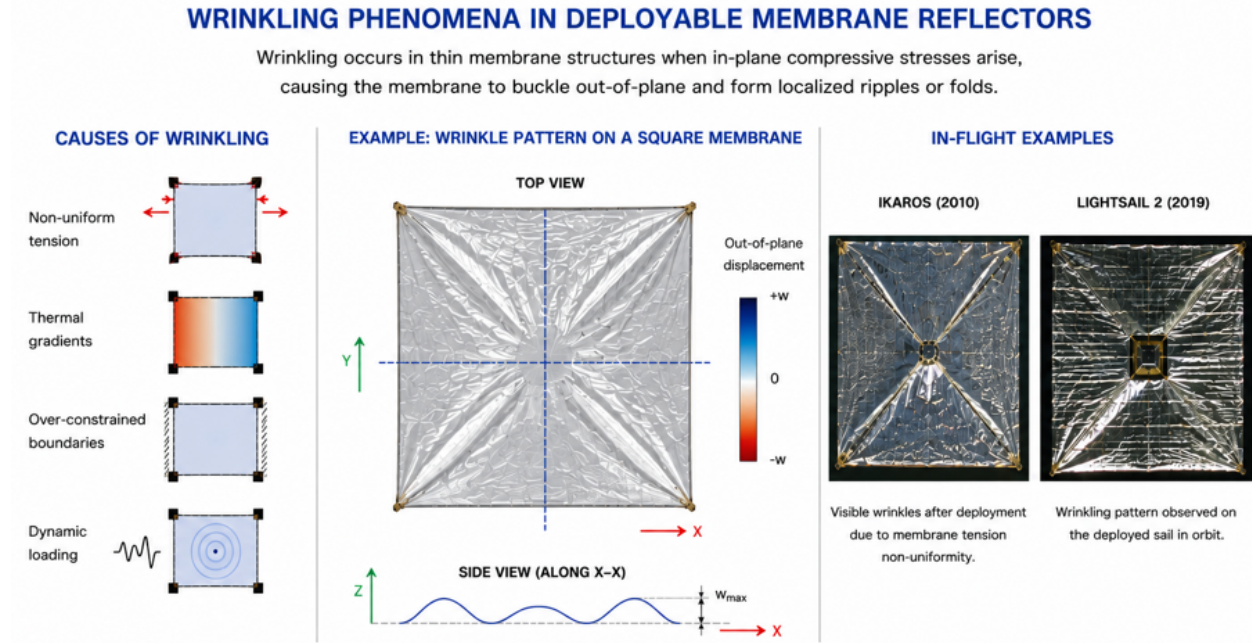


Figure 3.9: Schematic representation of wrinkling phenomena in large deployable membrane reflectors. The figure summarizes the principal causes of wrinkle formation, the resulting deformation patterns, and their effects on the structural and optical performance of thin membrane structures considering representative flight examples such as IKAROS[27] and LightSail 2[39]

The presence of wrinkles directly affects the functional performance of Deployable Membrane Reflectors. In optical applications, local out-of-plane deformations reduce surface accuracy and introduce wavefront errors that degrade imaging performance. For radio-frequency reflectors, wrinkles modify the reflector profile, decreasing antenna gain and increasing side lobes. In solar sails and Solar Radiation Management concepts, membrane deformation changes the local orientation of the reflective surface, altering the direction and magnitude of the radiation pressure acting on the spacecraft.

The severity of wrinkling depends on several design parameters, including membrane thickness, boom stiffness and reflector dimensions. Increasing membrane pretension generally reduces wrinkle amplitude by maintaining the membrane in a predominantly tensile stress state. However, excessive pretension also increases the structural loads transmitted to the supporting booms and deployment mechanisms, requiring heavier structural members. Consequently, the determination of the optimum pretension level represents a compromise between structural stability and overall system mass.

Several solutions have been proposed to minimize wrinkle formation in large deployable membranes. These include optimizing membrane pretension, increasing boom stiffness, introducing peripheral tensioning cables, tailoring membrane geometry, and employing active shape-control systems capable of adjusting the reflector configuration after deployment. Advances in composite supporting structures and adaptive tensioning mechanisms have considerably improved the capability of modern DMRs to maintain a stable reflective surface under varying operational conditions.

Although wrinkle formation cannot be completely eliminated, its effects can be substantially reduced through careful structural analysis and appropriate selection of the membrane architecture. For this reason, wrinkling analysis constitutes a fundamental step in the development of large Deployable Membrane Reflectors and is routinely incorporated into the structural verification process of modern membrane-based spacecraft.

3.5.3 Thermoelastic Effects

Thermoelastic effects represent one of the principal environmental challenges affecting Deployable Membrane Reflectors (DMRs). Owing to their extremely low thickness and large surface area, membrane structures rapidly respond to variations in the thermal environment, developing non-uniform temperature distributions that induce dimensional changes and modify the stress state of the reflector. These thermoelastic deformations may significantly alter the membrane geometry, compromising both structural stability and optical performance[9].

Thermoelastic Effects depends on several factors, such as:

- the distance from the Sun;
- the spacecraft attitude;
- membrane optical properties;
- external radiative sources.

Since solar radiation is perfectly uniform over the entire reflector, temperature gradients naturally develop across the membrane surface.

The dimensional variation produced by a temperature change is commonly approximated by

$$\Delta L = \alpha L \Delta T \quad (3.2)$$

where ΔL is the change in length, α is the coefficient of thermal expansion (CTE) of the membrane material, L is the initial length, and ΔT is the temperature variation.

Although this relationship appears simple, its implications for deployable membrane systems are significant. Even relatively small thermal expansions may generate measurable variations in membrane tension because of the very large dimensions and limited structural stiffness of the reflector. If different regions of the membrane experience different temperatures, differential expansion may produce local stress concentrations, modify the pretension distribution, and promote wrinkle formation.

Thermoelastic effects also can influence the support structure, in particular deployable booms are generally manufactured from different materials, their coefficients of thermal expansion may differ considerably. This mismatch generates additional internal stresses at the membrane-boom interfaces and may slightly alter the deployed geometry of the reflector. Consequently, the selection of compatible materials and the optimization of the structural architecture are essential to minimize thermoelastic distortions.

Then the severity of thermoelastic deformation depends strongly on the membrane material. Polyimide films such as Kapton and CP1 exhibit relatively low coefficients of thermal expansion and excellent dimensional stability over a wide temperature range, making them particularly suitable for deployable space structures. Metallic coatings also influence the thermal response by modifying the absorptivity and emissivity of the membrane surface, thereby affecting its equilibrium temperature under solar illumination [49].

Several mitigation strategies have been proposed to reduce thermoelastic effects. These include the selection of low-CTE materials, optimization of membrane coatings, improvement of structural symmetry, and careful control of the pretension applied during deployment. Advanced concepts also investigate adaptive structures capable of actively compensating for thermally induced deformations through distributed actuators or variable-tension mechanisms.

3.6 Technology Selection and Baseline Configuration

The previous sections reviewed the current state of the art of Deployable Membrane Reflectors (DMRs), analysing membrane materials, supporting structures, deployment mechanisms, and the structural stability of large deployable membrane systems. Although numerous technological solutions have been proposed and demonstrated over the past decades, no single architecture is universally optimal. The selection of the baseline configuration must therefore be driven by the specific requirements of the intended mission.

The objective of this work is the preliminary design of a Deployable Membrane Reflector for a Space-Based Solar Radiation Management mission operating near the Sun-Earth Lagrange Point L1.

Based on the analyses presented throughout this chapter, the baseline architecture has been selected according to the following design drivers:

- low structural mass and high area-to-mass ratio;
- compact stowed configuration compatible with existing launch vehicles;
- high deployment reliability for a single deployment event;
- sufficient structural stiffness to preserve membrane flatness;
- scalability to reflector dimensions of several tens of metres;
- high Technology Readiness Level (TRL) and demonstrated flight heritage.

The resulting technology selection is summarized in the following table.

Subsystem	Selected Technology	Selection Rationale
Membrane Material	Kapton HN	Excellent thermal stability and flight heritage
Reflective Coating	Aluminium	High solar reflectivity and low areal density
Supporting Structure	TRAC Composite Booms	Highest structural trade-off score
Deployment System	Passive Boom-Driven Deployment	Simple and reliable deployment
Membrane Geometry	Square Membrane	Uniform tension distribution and scalability

Table 3.5: Selected baseline technologies for the proposed Deployable Membrane Reflector.

Among the membrane materials trade off in the previous sections, Kapton HN has been selected owing to its excellent thermo-mechanical properties, resistance to ultraviolet radiation, and extensive use in space missions. Although newer materials such as CP1 exhibit improved dimensional stability, Kapton currently provides the best compromise between performance, availability, and technological maturity.

Then the comparison of support structures performed in Section 3.4 identified the TRAC boom as the most suitable architecture for the proposed mission. Its lightweight composite construction, high bending and torsional stiffness, compact packaging capability, and recent in-orbit validation provide the highest overall score among the structural concepts considered. The selected deployment strategy naturally follows from this choice, exploiting the passive self-deployment characteristics of rollable composite booms while minimizing the number of moving mechanical components.

A square membrane geometry has been adopted because it provides an efficient and well-balanced structural configuration. Four deployable booms support the membrane symmetrically, promoting a relatively uniform tension distribution and simplifying both the deployment sequence and the structural design. This configuration has also been successfully employed in several solar sail demonstrators, demonstrating its suitability and scalability for large deployable membrane systems.

Subsystem	Selected Technology	Selection Rationale
Membrane Material	Kapton HN	Excellent thermal stability and extensive flight heritage.
Reflective Coating	Aluminium	High solar reflectivity with low areal density.
Supporting Structure	TRAC Composite Booms	Highest score in the structural trade-off, providing an excellent balance between stiffness, mass, packaging efficiency, and deployment reliability.
Deployment System	Passive Boom-Driven Deployment	Simple, reliable, and fully compatible with rollable composite booms.
Membrane Geometry	Square Membrane	Provides uniform membrane tension and excellent scalability.

Table 3.6: Selected baseline technologies for the proposed Deployable Membrane Reflector.

The baseline configuration selected in this chapter therefore combines mature membrane materials, advanced composite supporting structures, and well-established deployment technologies into a coherent engineering solution. This architecture will serve as the reference configuration for the preliminary sizing, structural analyses, and system design activities presented in the next chapter.

Trade-Off analysis & Mission Concept Selection

4.1 Introduction

In the previous chapter the main technologies enabling the realization of large Deployable Membrane Reflectors (DMRs) have been presented, including membrane materials, supporting structures, deployment architectures, and the structural behaviour of lightweight membrane systems. Through a series of technology trade-off analyses, a baseline reflector configuration has been identified based on mature technologies with demonstrated flight heritage.

Having established the technological baseline, the next step consists in defining the mission concept in which the selected Deployable Membrane Reflector will operate. While the previous chapter focused on the design of the spacecraft itself, the present chapter addresses the system-level aspects of the mission, identifying the architecture that best satisfies the objectives of Space-Based Solar Radiation Management (SB-SRM).

Several mission concepts have been proposed in the literature to reduce the amount of solar radiation reaching the Earth, ranging from monolithic reflective shields and refractive lens systems to distributed constellations of spacecraft operating near the Sun–Earth Lagrange Point L1. These concepts differ considerably in terms of implementation complexity, scalability, technological maturity, operational robustness, and expected performance. Likewise, different orbital configurations can be adopted to maximize the effectiveness of the reflective system while minimizing station-keeping requirements and operational constraints.

The objective of this chapter is therefore to identify the most suitable mission concept for the proposed SB-SRM application through a structured systems engineering trade-off analysis. Candidate architectures are evaluated using a weighted decision matrix based on technical and operational criteria, including mission effectiveness, scalability, deployment feasibility, technology readiness, operational robustness, launch compatibility, and long-term sustainability.

Unlike the technology trade-off presented in Chapter 3, which focused on the selection of the most appropriate structural and deployment technologies, the present analysis is performed at the mission level. The selected DMR configuration is assumed as a fixed design input, while the trade-off concentrates on higher-level decisions such as the overall mission architecture, the operational orbit, and the deployment strategy of the complete system.

The outcome of this chapter is the definition of a baseline mission concept, including the selection of the most suitable solar radiation management architecture, the preferred operational orbit, and the principal mission requirements. These results provide the foundation for the preliminary mission design and system sizing activities developed in the following chapter.

Figure 4.1 summarizes the methodology adopted throughout the mission concept selection process.

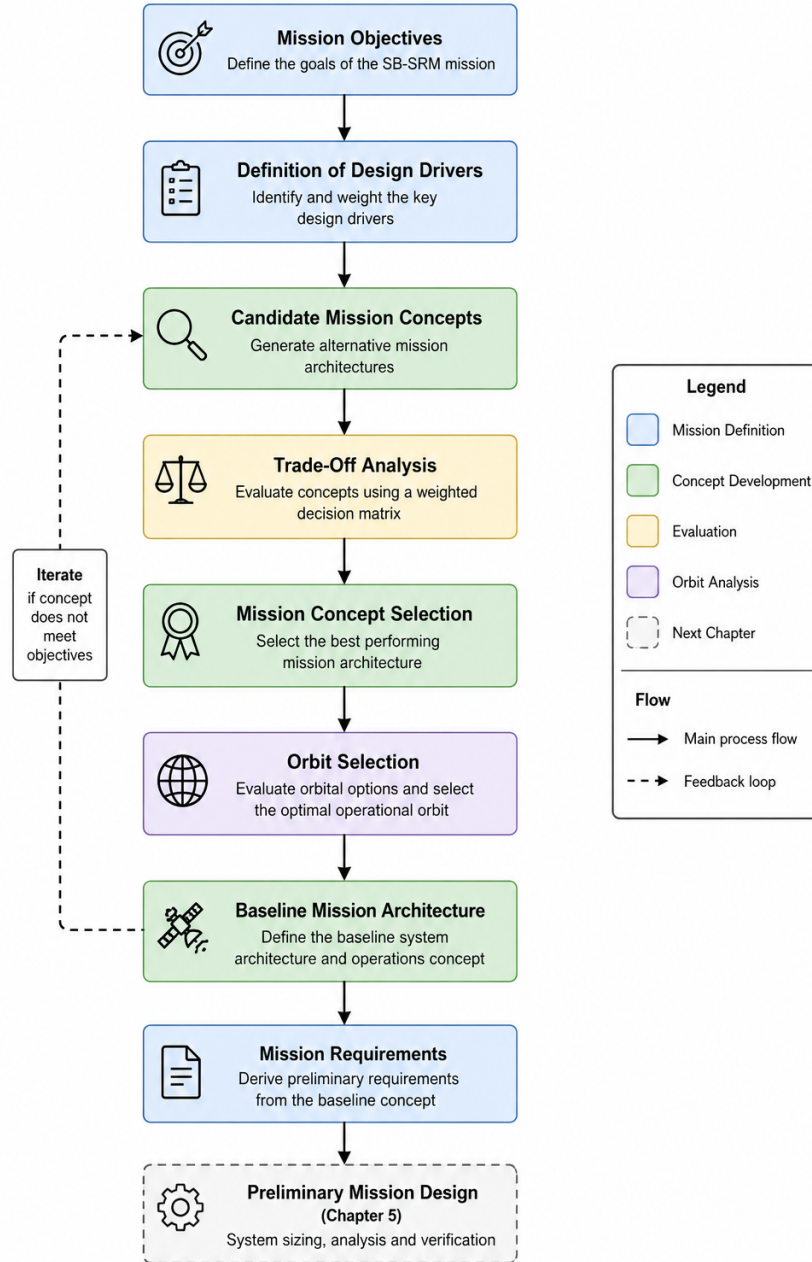


Figure 4.1: Methodology adopted for the mission concept selection process. Starting from the mission objectives, candidate concepts are identified and evaluated through a weighted trade-off analysis, leading to the definition of the baseline mission architecture.

4.2 Mission Objectives and Design Drivers

The mission concept proposed in this work aims to investigate the feasibility of a Space-Based Solar Radiation Management (SB-SRM) system employing Deployable Reflective Membrane Arrays (DRMAs) operating in the vicinity of the Sun-Earth L1 Lagrange point. The primary objective is to reduce a small fraction of the incoming solar radiation reaching the Earth by means of large lightweight reflective membranes capable of redirecting part of the incident solar flux before it reaches the terrestrial atmosphere.

Unlike conventional solar sail missions, where reflective membranes are primarily used to generate propul-

sion through Solar Radiation Pressure (SRP), the proposed architecture employs deployable membranes as passive optical elements. Their role is therefore to maximize the intercepted solar flux while maintaining structural stability, long operational lifetime, and compatibility with current and near-future space technologies.

The concept builds upon the technological heritage reviewed in Chapter 3, where deployable membrane technologies, supporting structures, deployment architectures, and membrane materials were studied with a dedicated technology trade-off analyses. Consequently, the present chapter assumes the selected technological baseline as a fixed design input and focuses on the system-level requirements governing the overall mission architecture.

The mission objectives adopted in this study are derived from previous investigations on SB-SRM concepts proposed by Early [1], Angel [14], and subsequent studies on large deployable membrane spacecraft and solar sails [9].

These objectives can be summarized as follows:

- Reduce a fraction of the incoming solar radiation through passive reflection;
- Maximize the effective reflective area while minimizing launch mass and stowed volume;
- Enable incremental deployment through a modular spacecraft architecture;
- Ensure long-term operation in the deep-space environment with minimal maintenance;
- Minimize operational complexity and station-keeping requirements;
- Maximize mission scalability by allowing the gradual expansion of the reflective array.

These objectives can be translated into a series of design drivers that will be employed throughout the trade-off analyses presented in the following sections. Unlike mission requirements, which represent mandatory conditions, design drivers express the characteristics that most strongly influence the overall quality of the selected mission architecture.

The principal design drivers considered in this work are:

- **Mission Effectiveness:** capability of reducing the incoming solar radiation reaching the Earth.
- **Scalability:** possibility of increasing the reflective area through the addition of independent membrane units.
- **Mass Efficiency:** maximization of deployed reflective area per unit launch mass.
- **Deployment Feasibility:** reliability and simplicity of the deployment sequence.
- **Technology Readiness Level (TRL):** preference for technologies already demonstrated through flight heritage.
- **Operational Robustness:** capability of maintaining functionality despite failures of individual spacecraft.
- **Launch Compatibility:** compatibility with existing and near-future launch systems.
- **Station-Keeping Requirements:** minimization of propulsion and attitude control effort.
- **Manufacturability:** feasibility of producing large numbers of identical spacecraft.
- **Cost Effectiveness:** optimization of the performance-to-cost ratio.

The identified design drivers represent the basis of the weighted trade-off methodology adopted in the following sections. Each candidate mission concept will be evaluated according to these criteria in order to identify the architecture providing the most balanced compromise between mission effectiveness, technological maturity, scalability, and long-term operational feasibility.

4.3 Candidate Mission Concepts

Several concepts have been proposed in the literature to reduce the amount of solar radiation reaching the Earth through the deployment of structures in the vicinity of the Sun-Earth L1 Lagrange point. Although all these concepts share the same objective, they differ significantly in terms of operating principle, technological requirements, scalability, and implementation complexity.

To identify the most suitable architecture for the proposed mission, four candidate concepts were selected for further evaluation. These concepts represent the most relevant solar radiation management solutions currently available in the literature and provide a suitable design space for the trade-off analysis.

4.3.1 Concept A: Monolithic Space Shields

The concept of a monolithic space shield represents the earliest approach in literature proposed for Space-Based Solar Radiation Management (SB-SRM). The fundamental idea consists of placing a single, extremely large reflective or partially opaque structure in the vicinity of the Sun-Earth Lagrange Point L1 in order to intercept a small fraction of the incoming solar radiation before it reaches the Earth's atmosphere. By slightly reducing the incident solar flux, the shield would produce a corresponding decrease in the global radiative forcing, potentially mitigating the effects of anthropogenic climate change[1].

The first study was presented by Early in 1989, who proposed a large thin-film structure positioned near the Sun-Earth L1 point to mitigate the greenhouse effect. In this pioneering work, the author demonstrated that even a relatively small reduction of the incoming solar irradiance could significantly influence the Earth's energy balance, opening the possibility of using space-based infrastructures as long-term climate engineering systems[1].

The operating principle of a monolithic shield is illustrated in Figure 4.2. Positioned close to the Sun-Earth line, the structure partially blocks or reflects the incoming solar radiation, thereby reducing the amount of energy reaching the Earth. In contrast to distributed concepts based on numerous independent spacecraft, the entire solar shading capability is concentrated within a single large structure.

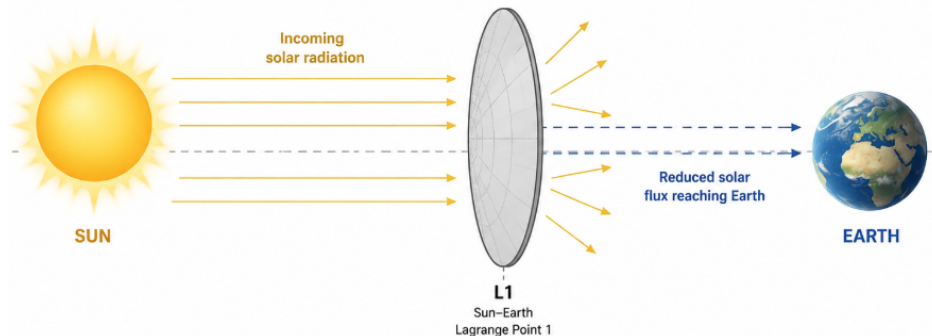


Figure 4.2: Conceptual representation of a monolithic space shield positioned near the Sun-Earth L1 point. The structure partially intercepts the incoming solar radiation, reducing the solar flux reaching the Earth. Adapted from[1].

The overall system architecture is very simple, requiring only one operational platform and eliminating the need for formation flying or constellation management. Furthermore, the optical performance can be directly related to the projected area of the shield, simplifying both mission analysis and system modelling.

Despite these advantages, the implementation of such a concept presents extraordinary technological challenges. The required dimensions should be enormous, with characteristic lengths extending over hundreds or even thousands of kilometres depending on the desired reduction of solar irradiance. Consequently, manufacturing, packaging, launch, deployment, and structural stabilization rapidly become impractical with current or foreseeable space technologies.

Although the monolithic space shield remains one of the most influential concepts in the history of SB-SRM for its innovative approach, it is generally regarded as a valuable theoretical reference rather than a practical engineering solution. The technological challenges associated with manufacturing, deployment, and long-term operation have progressively shifted research efforts toward modular and distributed architectures based on multiple independent spacecraft. These approaches exploit advances in deployable membrane technologies while providing improved scalability, redundancy, and operational flexibility, characteristics that make them considerably more attractive for future space-based climate mitigation missions.

4.3.2 Concept B: Distributed Optical Systems

An alternative approach to monolithic sunshield consists of replacing a single large structure with a distributed constellation of numerous lightweight spacecraft, each carrying an optical element capable of slightly modifying the propagation direction of the incoming solar radiation. Unlike reflective concepts, which reduce the solar flux by blocking or reflecting sunlight, distributed optical systems operate primarily through refraction or diffraction, redirecting a small fraction of the incident radiation away from the Earth.

The most influential proposal belonging to this category was introduced by Angel in 2006[14], who investigated the feasibility of deploying a cloud of approximately 10^{16} small spacecraft in the vicinity of the Sun-Earth L1 Lagrange point. Each spacecraft would carry a thin Fresnel lens designed to produce a very small angular deflection of the incoming solar rays. Even if the deviation generated by each individual element is extremely limited, the cumulative effect of the entire constellation would be sufficient to reduce the solar irradiance reaching the Earth by approximately 1.8%, a value considered adequate to compensate for the radiative forcing associated with a doubling of atmospheric CO₂ concentration.

Distributed optical systems present several important advantages. First of all the architecture that is modular and scalable. Additional units can be progressively launched to increase the overall effectiveness of the system, while the failure of individual spacecraft has only a negligible impact on the global performance. This distributed philosophy also simplifies manufacturing by enabling the mass production of identical spacecraft rather than requiring the realization of a single ultra-large structure.

Figure 4.3 present the operating principle of a distributed optical architecture. Instead of physically blocking the incoming radiation, each spacecraft slightly refracts the incident sunlight, producing a cumulative reduction of the solar flux reaching the Earth.

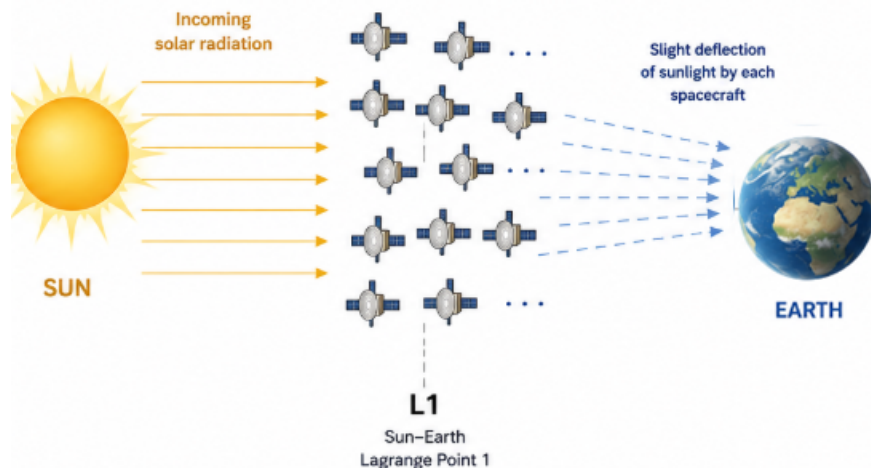


Figure 4.3: Conceptual representation of a distributed optical system operating near the Sun–Earth L1 point. Thousands of spacecraft equipped with lightweight optical elements collectively redirect a fraction of the incoming solar radiation away from the Earth. Adapted from [14].

Despite its attractive scalability, this concepts introduces significant challenges such as the deployment and long-term operation of trillions of spacecraft. Precise attitude determination and control are necessary

to ensure that each optical element maintains the required orientation with respect to both the Sun and the Earth. Furthermore, orbital perturbations caused by solar radiation pressure and gravitational effects continuously modify the relative positions of the spacecraft, making station-keeping a critical aspect of the mission.

Another important limitation concerns the TRL of the required optical elements. Although Fresnel lenses and diffractive optical devices are well-established technologies for terrestrial applications, their large-scale deployment in the harsh space environment has not yet been demonstrated. Long-term degradation due to ultraviolet radiation, contamination, thermal cycling, and micrometeoroid impacts remains an open research topic.

Nevertheless, distributed optical systems represent one of the most influential concepts proposed for Space-Based Solar Radiation Management. Their modular architecture, high scalability, and absence of extremely large structural components have strongly influenced many subsequent SB-SRM studies. Several concepts currently under investigation adopt similar distributed philosophies while replacing refractive optical elements with deployable reflective membranes, thereby exploiting the significant technological advances achieved in membrane spacecraft during the last two decades. This evolution naturally leads to the Deployable Reflective Membrane Array concept investigated in the present work.

4.3.3 Concept C: Dust Cloud Solar Shield

A third family of Space-Based Solar Radiation Management concepts is based on the use of particulate clouds rather than engineered space structures. Instead of deploying large reflectors or optical elements, these architectures propose the creation of a cloud of microscopic particles capable of scattering a fraction of the incoming solar radiation before it reaches the Earth. The attenuation mechanism therefore relies primarily on light scattering, with a minor contribution from absorption depending on the optical properties of the particles.

One of the first detailed investigations of this approach was presented by Bromley et al[42], who proposed the generation of an artificial dust cloud in the vicinity of the Sun-Earth L1 Lagrange point using material extracted from asteroids or the lunar surface. The concept exploits the large number of suspended particles to create an extended semi-transparent screen capable of reducing the solar irradiance reaching the Earth while avoiding the deployment of extremely large engineered structures.

The operating principle is illustrated in the next figure.

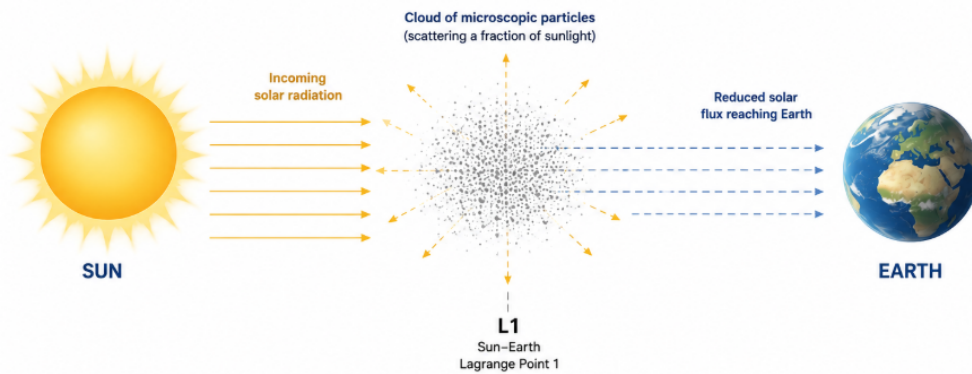


Figure 4.4: Conceptual representation of a particulate solar shield. A cloud of microscopic particles located near the Sun-Earth L1 point scatters part of the incoming solar radiation, reducing the solar flux reaching the Earth. Adapted from[42].

4.3.4 Concept D: Deployable Reflective Membrane Array

Among the various Space-Based Solar Radiation Management (SB-SRM) concepts proposed in the literature, Deployable Reflective Membrane Arrays (DRMAs) represent one of the most promising solutions from an engineering perspective. This concept employs a distributed constellation of spacecraft, each carrying a

large deployable reflective membrane. The cumulative reflective area generated by the entire constellation provides the required reduction of the solar irradiance while maintaining a modular, scalable, and fault-tolerant architecture.

The concept builds directly upon the technological developments achieved during the last two decades in the field of deployable membrane spacecraft. Missions such as IKAROS[27], NanoSail-D[22], LightSail 2[29], and the Advanced Composite Solar Sail System (ACS3)[40] have demonstrated the feasibility of deploying large lightweight membranes in space, progressively increasing both the Technology Readiness Level (TRL) and the confidence in deployable membrane technologies.

Their primary objective of the membrane is to reflect a small fraction of the incoming solar radiation away from the Earth, thereby contributing to a reduction of the global radiative forcing. Since each spacecraft operates independently, the overall system can be progressively expanded by launching additional reflector units over time.

The operating principle is illustrated in figure 4.5. A constellation of identical spacecraft is positioned in the vicinity of the Sun-Earth L1 point. Each spacecraft deploys a lightweight reflective membrane using the boom-driven architecture selected in Chapter 3. The combined reflective area of the constellation intercepts part of the incoming solar radiation, while the modular architecture distributes both the structural loads and the mission risk among multiple independent units.

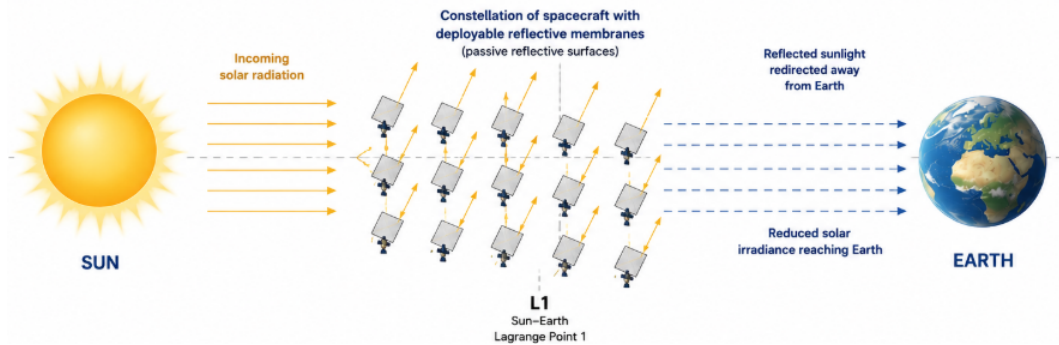


Figure 4.5: Conceptual representation of a Deployable Reflective Membrane Array (DRMA). Multiple spacecraft equipped with deployable reflective membranes operate near the Sun–Earth L1 point, collectively reducing the solar irradiance reaching the Earth.

Compared with the previously discussed architectures, Deployable Reflective Membrane Arrays offer several significant engineering advantages. First, the modular nature of the system enables incremental deployment. The mission does not require the simultaneous launch of the complete reflective area; instead, additional spacecraft may be deployed progressively, allowing the overall system performance to increase over time.

Then the distributed architecture greatly improves mission robustness. Since each spacecraft represents an independent functional unit, the failure of one or more reflectors has only a limited influence on the overall mission effectiveness. This intrinsic redundancy contrasts sharply with monolithic concepts, where the failure of a single structure would compromise the entire system.

Another important advantage derives from the maturity of deployable membrane technologies. As discussed in Chapter 3, lightweight polymeric membranes, composite booms, and boom-driven deployment systems have already accumulated significant flight heritage through numerous solar sail, drag sail, and deployable antenna missions. Consequently, the proposed architecture relies primarily on technologies that already exist or require only evolutionary rather than revolutionary developments.

Naturally, this architecture also introduces several technical challenges. First of all, precise attitude control is required to maintain the correct orientation of each reflective membrane with respect to both the Sun and the Earth. Furthermore, long-term station-keeping near L1 point requires continuous compensation of gravitational perturbations and solar radiation pressure. Collision avoidance, constellation management, and autonomous coordination among hundreds or thousands of spacecraft also become increasingly important as the constellation expands.

Despite these challenges, Deployable Reflective Membrane Arrays currently represent one of the most balanced solutions for future SB-SRM missions. Their combination of high scalability, technological maturity, incremental deployment capability, and operational robustness makes them particularly attractive for long-duration climate mitigation applications.

4.3.5 Mission Concept Trade-Off

Following the qualitative assessment of the candidate Space-Based Solar Radiation Management (SB-SRM) architectures presented in the previous sections, a structured trade-off analysis was performed to identify the mission concept providing the best overall compromise between mission effectiveness, technological feasibility, scalability, and long-term operational sustainability.

The purpose of the trade-off is not to identify the theoretically most effective concept, but rather the architecture that can realistically be implemented using existing or near-future space technologies. Consequently, the evaluation considers both engineering and operational aspects, adopting a systems engineering approach similar to those commonly employed during ESA and NASA Phase A mission studies.

Each candidate concept is evaluated using a weighted scoring methodology. Individual scores are assigned on a qualitative scale ranging from 1 to 5 (excellent), while weighting factors reflect the relative importance of each criterion with respect to the objectives of the proposed SB-SRM mission.

The evaluation criteria adopted in this study are summarized in Table 4.1.

Criteria	Purpose	Weight
Mission Effectiveness	Ability to reduce the incoming solar radiation reaching the Earth.	0.25
Scalability	Capability of increasing the total reflective area by adding new spacecraft.	0.15
Technology Readiness	Maturity of the enabling technologies and availability of flight heritage.	0.15
Deployment Feasibility	Complexity, reliability, and risk associated with the deployment process.	0.10
Operational Robustness	Tolerance to failures and long-term operational reliability.	0.10
Station-Keeping	Effort required to maintain the operational orbit near the Sun–Earth L1 point.	0.10
Manufacturability	Ease of manufacturing, assembly, and large-scale production.	0.05
Cost Effectiveness	Expected balance between mission performance and implementation cost.	0.10
Total		1.00

Table 4.1: Evaluation criteria adopted for the mission concept trade-off.

The resulting weighted trade-off matrix is reported in Table 4.2. The numerical scores are based on the current technological state of the art reviewed in Chapters 2 and 3 together with published SB-SRM studies [1, 14, 28, 9].

Concept	Effectiveness	Scalability	TRL	Deployment	Robustness	Station Keeping	Manufacturing	Cost	Score
Monolithic Shield	5	1	1	1	1	2	1	1	2.15
Distributed Optical System	4	5	2	2	4	3	3	2	3.35
Particulate Solar Shield	3	5	1	3	2	2	2	2	2.55
Deployable Reflective Membrane Array	4	5	4	4	5	4	4	4	4.20

Table 4.2: Mission concept trade-off matrix.

The trade off shows that the Deployable Reflective Membrane Array achieves the highest overall score. Although the monolithic shield offers excellent theoretical performance in terms of solar radiation interception, its extremely large dimensions make its practical implementation unrealistic using current engineering capabilities.

Distributed optical systems provide excellent scalability and intrinsic redundancy. Nevertheless, their implementation requires the deployment and coordinated control of trillions of spacecraft equipped with lightweight refractive optical elements, representing a technological challenge well beyond current space engineering capabilities.

The Deployable Reflective Membrane Array combines the principal advantages of distributed architectures with technologies that already possess a significant flight heritage. As discussed in Chapter 3, deployable membrane structures, composite booms, lightweight polymeric membranes, and boom-driven deployment systems have all been successfully demonstrated through missions such as IKAROS, NanoSail-D, LightSail 2, and ACS3. This technological heritage substantially reduces implementation risk while maintaining excellent scalability and operational robustness.

Another important advantage of the DRMA architecture is its incremental deployment capability. Since the reflective area is distributed among numerous independent spacecraft, the mission can progressively increase its effectiveness as additional units are launched. Furthermore, individual spacecraft failures have only a limited influence on overall mission performance, significantly improving system resilience compared to monolithic architectures.

Based on these results, the Deployable Reflective Membrane Array is selected as the baseline mission concept for the remainder of this work.

4.3.6 Baseline Concept Selection

Based on the results of the trade-off analysis, the Deployable Reflective Membrane Array architecture is selected as the baseline mission concept for further development.

The concept provides the best overall balance between performance, scalability, deployment feasibility, technological maturity, and operational robustness. In addition, it represents a realistic evolution of existing deployable membrane technologies while maintaining sufficient flexibility to support future large-scale implementations.

The selected baseline architecture will therefore constitute the starting point for the preliminary mission design presented in Chapter 4.

4.4 Orbit Selection Trade-Off

The performance of a space-based solar radiation management system is strongly influenced by the choice of the operational orbit. Since the primary objective of the proposed mission is to intercept and redirect a fraction of the incoming solar radiation before it reaches Earth, the selected orbit must maximize shading effectiveness while maintaining acceptable station-keeping requirements and long-term operational stability.

Several orbital configurations have been proposed in the literature for missions operating in the vicinity of the Sun–Earth L1 Lagrange point. These include conventional Halo and Lissajous orbits, as well as dis-

placed and artificial equilibrium orbits enabled by continuous non-gravitational forces such as solar radiation pressure.

To identify the most suitable operational configuration for the proposed Deployable Reflective Membrane Array (DRMA), a trade-off analysis was performed considering four candidate orbit families:

1. L1 Halo Orbit;
2. L1 Lissajous Orbit;
3. Displaced Non-Keplerian Orbit;
4. Artificial Equilibrium Orbit.

A schematic representation of the candidate orbital configurations is shown in Figure 4.6.

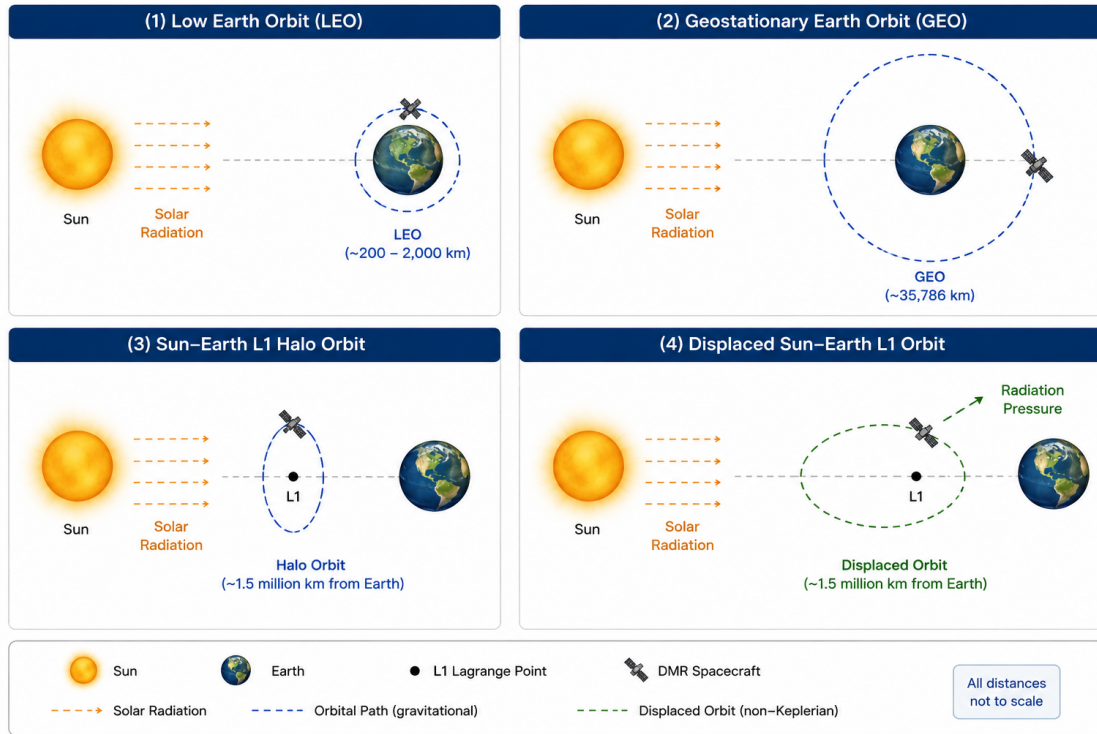


Figure 4.6: Candidate orbital configurations considered for the mission architecture.

4.4.1 L1 Halo Orbit

Halo orbits are three-dimensional periodic solutions of the Circular Restricted Three-Body Problem (CR3BP) around the Sun-Earth L1 point. These trajectories have been successfully employed by several missions, including SOHO and Genesis [5].

The primary advantages of Halo orbits are their extensive flight heritage and well-established operational procedures. However, the periodic motion around L1 causes the spacecraft to spend part of its orbit away from the Sun-Earth line, reducing the effectiveness of a shading system.

4.4.2 L1 Lissajous Orbit

Lissajous orbits represent quasi-periodic trajectories around the L1 point and are commonly used for scientific missions requiring stable observation conditions.

Compared with Halo orbits, Lissajous trajectories offer greater flexibility and can reduce station-keeping requirements. Nevertheless, their large excursions around the nominal equilibrium point also limit the achievable solar interception efficiency.

4.4.3 Displaced Non-Keplerian Orbit

Displaced orbits are non-Keplerian trajectories maintained through continuous acceleration generated by solar radiation pressure or low-thrust propulsion systems [6].

Unlike conventional Halo and Lissajous trajectories, displaced orbits allow the spacecraft to remain closer to the Sun–Earth line, thereby improving the effectiveness of the solar shading system. Furthermore, the reflective membranes themselves may contribute to orbit maintenance through solar radiation pressure.

The main disadvantage of this solution is the increased complexity associated with orbit control and long-term station keeping.

4.4.4 Artificial Equilibrium Orbit

Artificial equilibrium points are generated when the force produced by solar radiation pressure balances part of the gravitational forces acting on the spacecraft [19].

This approach allows the operational location to be shifted sunward with respect to the natural L1 point, maximizing the intercepted solar flux. Such configurations are particularly attractive for solar sail and reflective membrane missions because they directly exploit the interaction between the reflective surface and solar radiation.

However, artificial equilibrium orbits require continuous attitude control and are highly dependent on the optical properties and orientation of the reflective membranes.

4.4.5 Evaluation Criteria

The candidate orbit families were evaluated using the following criteria:

- Shading effectiveness;
- Station-keeping requirements;
- Operational stability;
- Technological maturity;
- Compatibility with reflective membrane systems.

The resulting qualitative assessment is summarized in Table 4.3.

Orbit	Shading	Stability	TRL	SRP Compatibility	Total
Halo Orbit	3	5	5	3	4.0
Lissajous Orbit	3	4	5	3	3.8
Displaced Orbit	5	3	3	5	4.3
Artificial Equilibrium Orbit	5	3	2	5	4.1

Table 4.3: Qualitative comparison of candidate orbital configurations.

4.4.6 Selected Orbit Configuration

The trade-off analysis indicates that displaced non-Keplerian orbits provide the most favorable balance between shading effectiveness and compatibility with deployable reflective membrane technologies.

Unlike conventional Halo and Lissajous trajectories, displaced orbits allow the reflective membrane array to remain closer to the Sun–Earth line, thereby maximizing the intercepted solar radiation. Furthermore, the continuous solar radiation pressure acting on the membrane surfaces can be exploited as part of the orbit maintenance strategy.

For these reasons, the displaced orbit configuration is selected as the baseline operational orbit for the preliminary mission design developed in Chapter 4. A more detailed analysis of the orbital dynamics and station-keeping requirements is presented in the subsequent design phase.

4.5 Preliminary Mission Requirements

The trade-off analyses presented in the previous sections identified the Deployable Reflective Membrane Array (DRMA) operating in a Sun–Earth L1 halo orbit as the baseline mission concept for the proposed Space-Based Solar Radiation Management (SB-SRM) system. Before proceeding to the preliminary spacecraft design, it is necessary to define the high-level mission requirements that will govern the subsequent engineering activities.

At this stage of the design process, the requirements are intentionally expressed at system level and do not represent detailed subsystem specifications. Instead, they establish the principal performance objectives and engineering constraints that the mission architecture must satisfy throughout its operational lifetime.

The preliminary mission requirements have been derived from three complementary sources:

- the scientific objectives of Space-Based Solar Radiation Management discussed in Chapter 2;
- the technology assessment and baseline configuration established in Chapter 3;
- the mission concept trade-off performed in the present chapter.

Based on these considerations, the principal mission requirements adopted in this work are summarized in Table 4.4.

Requirement	Category	Description
Solar radiation mitigation	Mission	The system shall reduce a fraction of the incoming solar radiation reaching the Earth through passive reflection.
Operational orbit	Mission	The spacecraft constellation shall operate in the vicinity of the Sun–Earth L1 halo orbit.
Mission architecture	System	The mission shall employ a distributed constellation of modular deployable membrane spacecraft.
Reflective surface	Payload	Each spacecraft shall deploy a lightweight reflective membrane using a boom-supported architecture.
Scalability	System	The architecture shall allow incremental expansion through the launch of additional spacecraft.
Operational lifetime	Mission	The spacecraft shall support long-duration operation under the deep-space environment.
Technology maturity	Programmatic	Preference shall be given to technologies with demonstrated flight heritage.
Reliability	System	The architecture shall remain operational despite the failure of individual spacecraft.
Launch compatibility	Programmatic	The spacecraft shall be compatible with existing or near-future launch vehicles.

Table 4.4: Preliminary mission requirements for the proposed SB-SRM mission.

The proposed requirements intentionally remain independent of detailed subsystem implementation. Parameters such as membrane dimensions, boom geometry, structural sizing, attitude control strategy, and propulsion system characteristics will be defined during the preliminary mission design presented in the following chapter.

Overall, these requirements establish a coherent engineering framework that translates the high-level objectives of Space-Based Solar Radiation Management into measurable design constraints. They ensure consistency between the scientific objectives, the selected mission concept, and the technological baseline adopted throughout this work.

The mission concept defined in this chapter provides the baseline for the subsequent preliminary mission design.

The following chapter therefore focuses on the engineering implementation of the selected architecture, describing the overall mission configuration, the spacecraft preliminary design, and the principal operational aspects required to realize the proposed Deployable Reflective Membrane Array mission.

Preliminary Mission Design

5.1 Introduction

The previous chapter established the baseline mission concept for the proposed Space-Based Solar Radiation Management (SB-SRM) mission through a structured systems engineering trade-off process. After evaluating several candidate architectures, the Deployable Reflective Membrane Array (DRMA) was selected as the preferred solution due to its favourable compromise between mission effectiveness, technological maturity, scalability, and operational robustness. Furthermore, the Sun-Earth L1 halo orbit was identified as the most suitable operational environment, providing continuous solar interception while limiting station-keeping requirements.

Having defined the overall mission architecture, the next step consists in translating the selected concept into a preliminary engineering design. In accordance with the objectives of a Phase A conceptual study, this chapter does not aim to provide a detailed subsystem design or complete engineering sizing. Instead, it defines the preliminary configuration of the mission by integrating the technological choices presented in Chapter 3 with the mission concept selected in Chapter 4.

The preliminary mission design focuses on the identification of the principal architectural elements required to implement the proposed SB-SRM mission. Particular attention is devoted to the overall mission architecture, the preliminary spacecraft configuration, and the operational concept governing the deployment and long-term operation of the deployable membrane reflector constellation.

The baseline spacecraft considered throughout this chapter adopts the technology selected during the structural trade-off analysis presented in Chapter 3. The reflector consists of a lightweight aluminized Kapton membrane supported by four TRAC composite booms deployed through a boom-driven deployment mechanism. The spacecraft is assumed to operate as an independent three-axis stabilized platform equipped with the subsystems necessary to perform attitude control, power generation, communications, and onboard data handling.

Unlike traditional spacecraft missions, the proposed SB-SRM architecture relies on a distributed constellation rather than on a single large platform. Consequently, the overall mission performance results from the cumulative contribution of multiple identical spacecraft operating cooperatively near the Sun-Earth L1 point. This modular philosophy improves scalability, increases fault tolerance, and enables the progressive expansion of the reflective area through the launch of additional spacecraft over the mission lifetime.

The objective of this chapter is to define the preliminary mission configuration resulting from the conceptual design analysis carried out in the previous chapters. The discussion begins with an overview of the selected mission architecture, followed by the description of the spacecraft preliminary configuration and the principal operational phases characterizing the mission lifecycle.

In figure 5.1 the transition from the conceptual design activities presented in the previous chapters to the preliminary mission design developed in this chapter has been described.

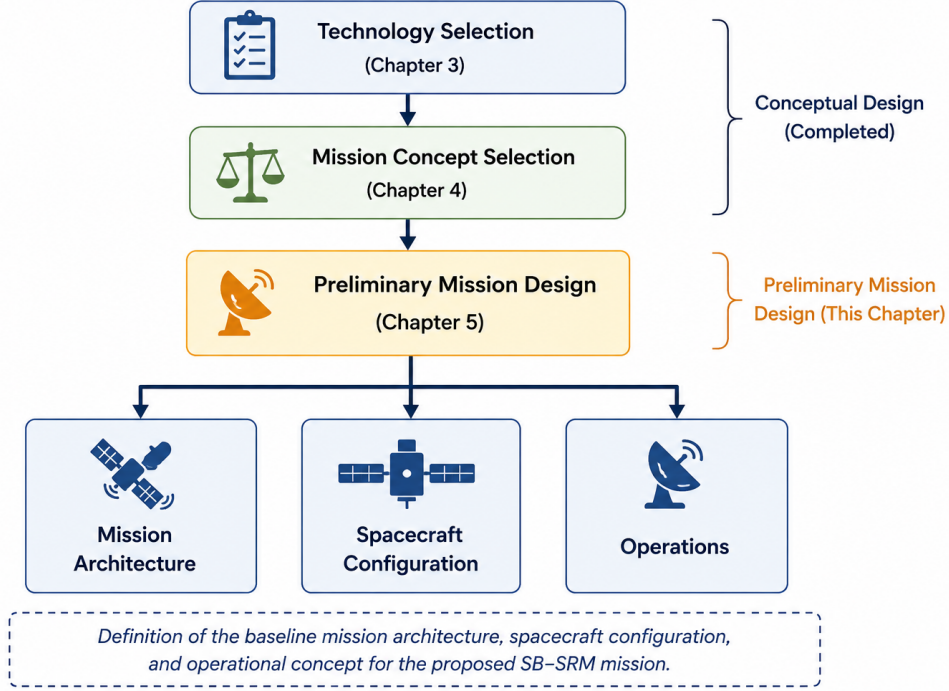


Figure 5.1: Transition from the conceptual design phase to the preliminary mission design. The technology baseline and mission concept identified in Chapters 3 and 4 constitute the starting point for the preliminary definition of the proposed SB-SRM mission.

5.2 Mission Overview

The conceptual design activities presented in the previous chapters resulted in the definition of a baseline mission architecture for a Space-Based Solar Radiation Management (SB-SRM) system based on Deployable Reflective Membrane Arrays (DRMAs). The proposed mission aims to demonstrate the feasibility of employing a modular constellation of spacecraft equipped with lightweight deployable membrane reflectors to partially reduce the solar irradiance reaching the Earth.

Unlike traditional solar sail missions, where the reflective membrane is primarily exploited to generate propulsive forces through Solar Radiation Pressure (SRP), the proposed spacecraft operates as a passive reflective platform. The deployed membrane is designed to redirect a small fraction of the incident solar radiation away from the Earth while maintaining structural stability and long-term operational capability within the Sun–Earth L1 environment.

The mission adopts a distributed architecture composed of multiple identical spacecraft rather than a single monolithic reflector. This solution was selected following the trade-off analysis presented in Chapter 4, as it provides significant advantages in terms of scalability, manufacturing, deployment flexibility, and operational robustness. Each spacecraft contributes independently to the overall reflective area, allowing the constellation to be progressively expanded through the launch of additional units.

The baseline mission architecture assumes that the spacecraft operate in a halo orbit around the Sun–Earth L1 Lagrange point. This location enables continuous exposure to the incoming solar radiation while maintaining an uninterrupted line of sight towards both the Sun and the Earth. Consequently, the reflective membranes remain continuously illuminated, maximizing the effectiveness of the proposed Solar Radiation Management strategy.

From a system engineering perspective, the proposed mission can be divided into four principal segments:

- **Launch Segment**, responsible for delivering the spacecraft to the transfer trajectory towards the operational orbit;

- **Transfer and Deployment Segment**, during which the spacecraft reaches the Sun–Earth L1 region and performs the deployment of the membrane reflector;
- **Operational Segment**, consisting of nominal attitude control, station-keeping, reflector pointing, and health monitoring activities;
- **End-of-Life Segment**, including spacecraft disposal and constellation replacement strategies.

The principal characteristics of the selected mission architecture are summarized in Table 5.1.

Parameter	Selected Configuration
Mission Objective	Space-Based Solar Radiation Management (SB-SRM)
Mission Concept	Deployable Reflective Membrane Array (DRMA)
Operational Orbit	Sun–Earth L1 Halo Orbit
Mission Architecture	Distributed spacecraft constellation
Reflector Type	Deployable reflective membrane
Supporting Structure	Four TRAC composite booms
Deployment Method	Boom-driven deployment
Membrane Material	Aluminized Kapton
Attitude Control	Three-axis stabilized spacecraft
Technology Heritage	IKAROS, NanoSail-D, LightSail 2, ACS3

Table 5.1: Summary of the preliminary mission architecture.

The preliminary mission architecture defined in this section establishes the overall framework adopted throughout the remainder of this chapter. The following sections progressively refine the mission by describing the spacecraft configuration, the operational concept, and the principal engineering assumptions underlying the proposed SB-SRM system.

5.3 Mission Architecture

The proposed Space-Based Solar Radiation Management (SB-SRM) mission adopts a distributed system architecture composed of multiple identical Deployable Reflective Membrane Array (DRMA) spacecraft operating cooperatively near the Sun–Earth L1 halo orbit. Rather than relying on a single large reflective structure, the total reflective surface is distributed among a constellation of modular spacecraft, each contributing independently to the overall mission objective.

The distributed architecture was selected following the mission concept trade-off presented in Chapter 4, as it provides superior scalability, operational robustness, manufacturability, and incremental deployment capability compared with alternative SB-SRM concepts. The modular design also enables progressive expansion of the reflective area by launching additional spacecraft throughout the mission lifetime, reducing both the initial implementation cost and the overall mission risk.

From a systems engineering perspective, the proposed mission architecture can be divided into four principal segments:

- **Launch Segment**, responsible for injecting the spacecraft into the transfer trajectory towards the Sun–Earth L1 region.
- **Space Segment**, consisting of the constellation of Deployable Reflective Membrane Array spacecraft operating in the selected halo orbit.
- **Ground Segment**, responsible for mission planning, spacecraft monitoring, command uplink, telemetry reception, and constellation management.

- **Operations Segment**, including reflector deployment, attitude control, orbit maintenance, health monitoring, and end-of-life disposal activities.

Figure 5.2 illustrates the overall architecture adopted for the proposed mission.

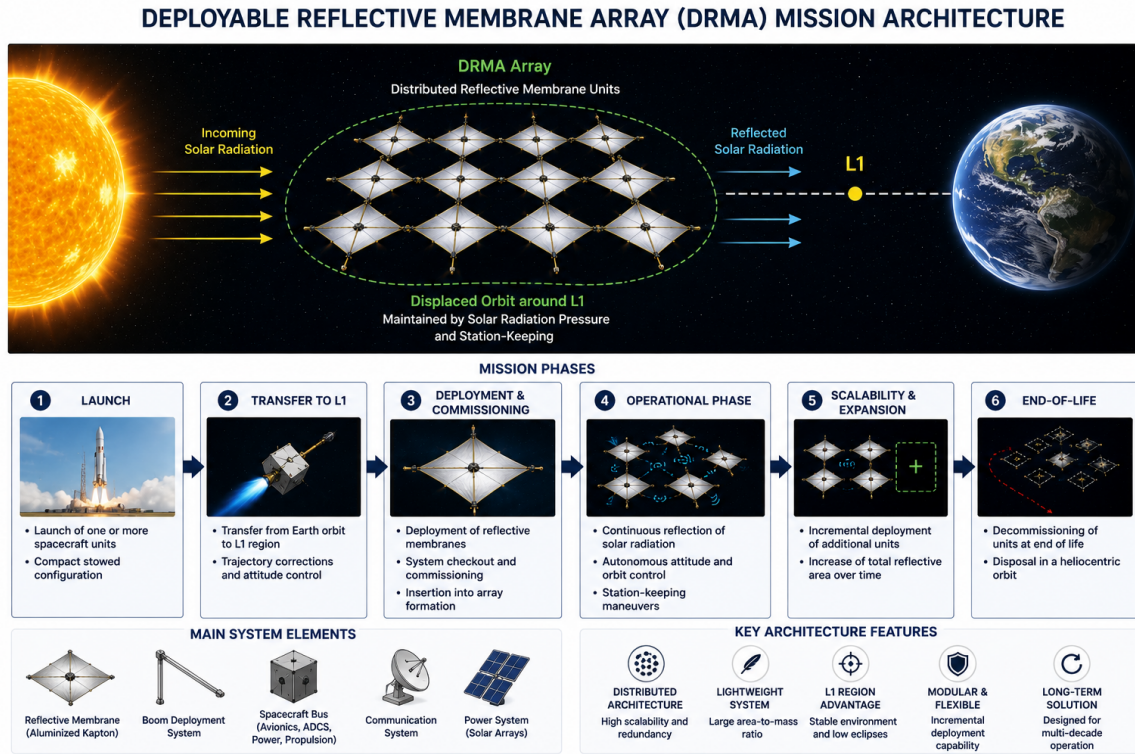


Figure 5.2: Overall architecture of the proposed Space-Based Solar Radiation Management mission. The system is composed of four segments: launch, space, ground, and mission operations.

The interaction between the different mission segments is summarized in Table 5.2.

Mission Segment	Primary Functions
Launch Segment	Launch vehicle integration, orbit injection, spacecraft separation and transfer initiation.
Space Segment	Deployable Reflective Membrane Array constellation operating near the Sun–Earth L1 halo orbit.
Ground Segment	Mission planning, spacecraft commanding, telemetry reception, orbit determination, and constellation supervision.
Operations Segment	Transfer, reflector deployment, station-keeping, attitude control, payload operations, health monitoring, and end-of-life disposal.

Table 5.2: Mission architecture segments and principal functions.

The modular organization of the mission considerably simplifies future expansion of the system. Since all spacecraft share a common platform and identical subsystem architecture, new reflector units can be introduced without requiring modifications to the existing constellation. This feature represents one of the principal advantages of the proposed distributed approach, enabling gradual increases of the total reflective area while maintaining operational continuity.

Furthermore, the distributed configuration inherently improves mission resilience. The loss or degradation of individual spacecraft produces only a minor reduction in the total reflective area, allowing the

mission to continue nominal operations despite isolated failures. This characteristic represents a substantial improvement over monolithic shielding concepts, where a single structural failure could compromise the entire mission.

Overall, the selected architecture combines technological maturity with operational flexibility, providing a scalable engineering solution that is consistent with current developments in deployable membrane spacecraft and future large-scale distributed space infrastructures.

5.4 Preliminary Spacecraft Configuration

The spacecraft adopted in the present preliminary mission design is based on a modular architecture specifically conceived to support the deployment and operation of a large Deployable Reflective Membrane (DRM) in the vicinity of the Sun–Earth L1 point. The configuration directly derives from the technology selection performed in Chapter 3 and from the mission concept identified in Chapter 4, integrating only technologies with significant flight heritage and adequate Technology Readiness Levels (TRLs).

The primary payload consists of a lightweight square reflective membrane manufactured from aluminized Kapton and supported by four Tape-Rolled Assembled Composite (TRAC) booms. The reflector is deployed through a boom-driven mechanism, allowing the membrane to unfold in a controlled and reliable manner while minimizing structural complexity. This configuration was selected following the technology trade-off analysis presented in Chapter 3, where it demonstrated the best compromise between structural efficiency, deployment reliability, scalability, and technological maturity.

The spacecraft bus accommodates all the subsystems required to support the deployment, operation, and long-term maintenance of the reflector. These include the Electrical Power System (EPS), the Attitude Determination and Control System (ADCS), the Command and Data Handling subsystem (C&DH), the Telecommunication subsystem (TT&C), and the Propulsion System required for orbit insertion and station-keeping maneuvers.

A three-axis stabilized attitude control architecture is assumed to maintain the correct orientation of the reflective membrane with respect to the Sun. Accurate attitude control is essential to maximize the reflective efficiency while minimizing structural oscillations induced by Solar Radiation Pressure (SRP). The spacecraft continuously adjusts its orientation through the coordinated action of reaction wheels and attitude sensors, while small propulsion corrections compensate for long-term orbital perturbations.

Figure 5.3 illustrates the preliminary spacecraft configuration and identifies the principal subsystems composing the proposed platform.

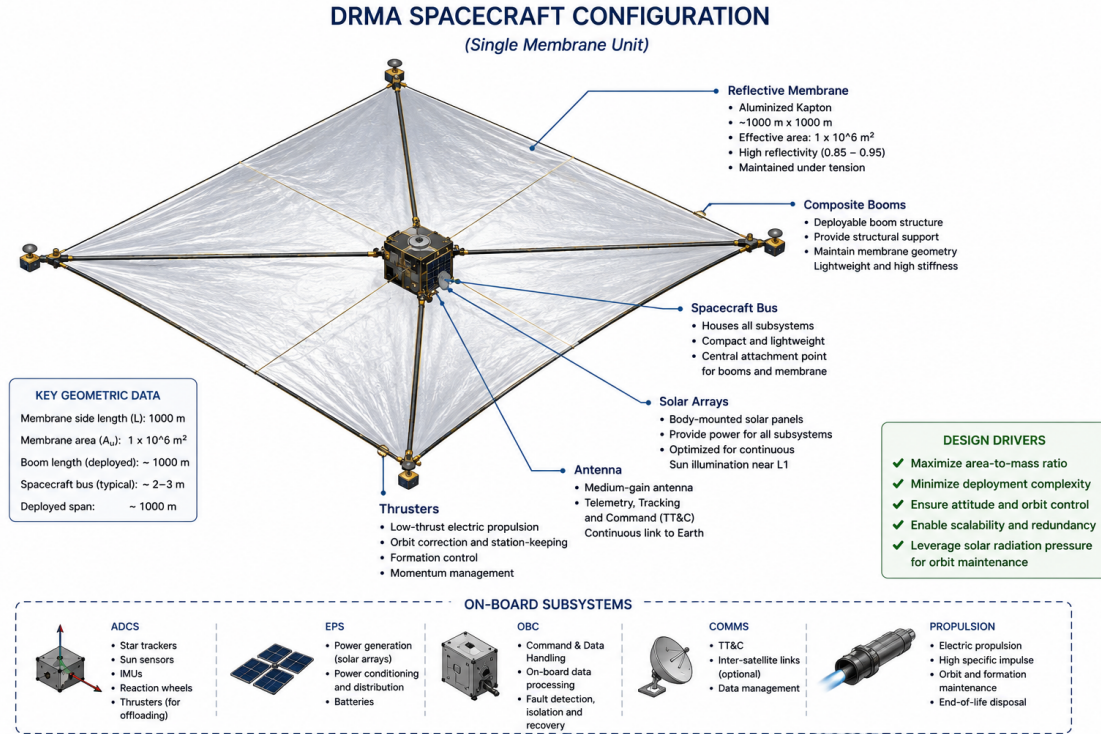


Figure 5.3: Preliminary configuration of the proposed Deployable Reflective Membrane spacecraft highlighting the principal structural and functional subsystems.

The principal subsystems adopted in the preliminary design are summarized in Table 5.3.

Subsystem	Selected Solution	Primary Function
Payload	Deployable reflective membrane	Partial reflection of incoming solar radiation.
Supporting Structure	Four TRAC composite booms	Membrane deployment and structural support.
Deployment System	Boom-driven mechanism	Controlled deployment of the reflector.
ADCS	Three-axis stabilized platform	Attitude determination and reflector pointing.
EPS	Body-mounted solar arrays and batteries	Electrical power generation and storage.
TT&C	High-gain communication system	Telemetry, tracking, and command.
C&DH	On-board computer	Spacecraft monitoring and subsystem coordination.
Propulsion	Low-thrust propulsion system	Orbit insertion and station-keeping.

Table 5.3: Preliminary spacecraft subsystem configuration.

Although the present work focuses primarily on the conceptual design of the deployable membrane reflector, the proposed spacecraft configuration demonstrates the feasibility of integrating mature membrane technologies with conventional spacecraft subsystems. The resulting platform constitutes a realistic engineering baseline for future developments aimed at the implementation of large-scale Space-Based Solar Radiation Management missions.

5.4.1 Reflective Membrane Sizing

The effectiveness of the proposed Deployable Reflective Membrane Array (DRMA) is directly related to the total reflective area deployed in the vicinity of the Sun–Earth L1 point. Consequently, the sizing of the reflective membrane system represents one of the most important aspects of the preliminary mission design.

The objective of this section is to establish a first-order estimate of the membrane area required to achieve a measurable reduction in the solar radiation reaching Earth and to determine the corresponding number of membrane units composing the distributed array.

5.4.2 Solar Flux Reduction Requirement

The average solar irradiance incident on the Earth's atmosphere, commonly referred to as the Solar Constant, is approximately [8]

$$S_0 = 1361 \text{ W/m}^2$$

A solar radiation management system located near the Sun–Earth L1 point aims to reduce this value by intercepting and redirecting a fraction of the incoming solar radiation.

For a preliminary analysis, a target reduction factor η is introduced:

$$\eta = \frac{\Delta S}{S_0}$$

where:

- S_0 is the solar constant;
- ΔS is the desired reduction in solar irradiance.

Previous studies have shown that even small reductions of the incoming solar flux could produce significant climatic effects [14]. For the purposes of this preliminary design, a target attenuation of

$$\eta = 0.5\%$$

is assumed.

5.4.3 Required Shaded Area

Assuming that the reflective membrane array intercepts a fraction of the solar radiation corresponding to the ratio between the membrane area and the Earth's projected cross-sectional area, the required reflective area can be approximated as

$$A_{req} = \eta A_E$$

where

$$A_E = \pi R_E^2$$

is the Earth's projected area.

Using

$$R_E = 6371 \text{ km}$$

the projected area becomes

$$A_E \approx 1.275 \times 10^{14} \text{ m}^2$$

and therefore

$$A_{req} = 0.005 \times 1.275 \times 10^{14}$$

$$A_{req} \approx 6.37 \times 10^{11} \text{ m}^2$$

This value represents the theoretical reflective area required to achieve a global solar flux reduction of approximately 0.5%.

5.4.4 Membrane Unit Definition

Rather than employing a monolithic reflective structure, the proposed mission utilizes a distributed architecture composed of multiple deployable membrane units.

Each unit is assumed to consist of a square reflective membrane supported by four deployable booms. For the preliminary sizing exercise, a membrane side length of

$$L = 1000 \text{ m}$$

is assumed.

The reflective area of a single unit is therefore

$$A_u = L^2$$

which yields

$$A_u = 1 \times 10^6 \text{ m}^2$$

corresponding to one square kilometre of reflective area per spacecraft.

5.4.5 Number of Membrane Units

The total number of spacecraft required to achieve the target reflective area can be estimated as

$$N = \frac{A_{req}}{A_u}$$

which results in

$$N = \frac{6.37 \times 10^{11}}{1 \times 10^6}$$

$$N \approx 6.37 \times 10^5$$

or approximately

$$N \approx 637\,000$$

membrane units.

This result highlights the enormous scale associated with planetary-scale solar radiation management systems and confirms the importance of adopting highly scalable and modular architectures.

5.4.6 Reflectivity Effects

The previous calculation assumes perfect interception and reflection of incoming solar radiation. In reality, the effectiveness of the membrane depends on its optical properties.

The effective reflective area can be expressed as

$$A_{eff} = C_R A$$

where

- A is the physical membrane area;

- C_R is the reflectivity coefficient.

For aluminized Kapton membranes, typical values are

$$0.85 < C_R < 0.95$$

depending on coating characteristics and degradation effects [6].

Consequently, the actual deployed area may need to be larger than the theoretical value estimated above.

5.4.7 Scalability Considerations

The sizing exercise clearly demonstrates that a practical implementation of a solar radiation management system cannot be realized through a single spacecraft or a monolithic structure. Instead, the system must be progressively deployed through a large number of modular membrane units.

One of the main advantages of the DRMA architecture is that the total reflective area scales linearly with the number of deployed spacecraft:

$$A_{tot} = N A_u$$

allowing the system to be incrementally expanded over time.

This capability represents a major advantage compared to monolithic shielding concepts and was one of the primary factors leading to the selection of the DRMA architecture during the trade-off analysis presented in Chapter 3.

5.4.8 Summary

The preliminary sizing analysis provides a first-order estimate of the reflective area required to achieve meaningful solar radiation attenuation. Although the resulting area requirements are extremely large, the calculations confirm the suitability of a distributed Deployable Reflective Membrane Array architecture for such applications.

The membrane dimensions and unit configuration derived in this section will be used in the following sections to define the spacecraft architecture, deployment strategy, and overall system performance.

5.5 Mission Operations

Following launch, the proposed Space-Based Solar Radiation Management (SB-SRM) mission is carried out through a sequence of operational phases that progressively lead the spacecraft from Earth to its nominal operating configuration near the Sun–Earth L1 halo orbit. Each phase is characterized by specific operational objectives and spacecraft activities, ensuring the successful deployment and long-term operation of the Deployable Reflective Membrane Array (DRMA).

The complete mission timeline adopted in this preliminary design is illustrated in Figure 5.4. The sequence includes launch, transfer, orbit insertion, membrane deployment, commissioning, nominal operations, and end-of-life disposal.

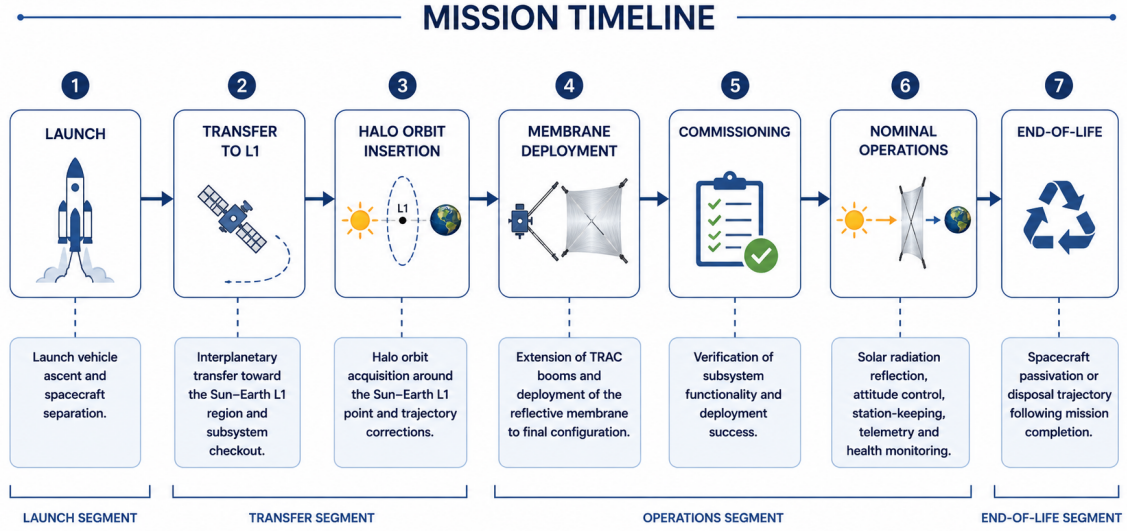


Figure 5.4: Operational timeline of the proposed SB-SRM mission from launch to end-of-life.

After launch, the spacecraft is injected into an interplanetary transfer trajectory toward the Sun–Earth L1 region. During this phase, the spacecraft remains in its stowed launch configuration, with the deployable membrane securely folded around the spacecraft bus and the supporting booms maintained within their deployment mechanisms. Initial subsystem checkout, attitude stabilization, and communication link verification are performed shortly after spacecraft separation from the launch vehicle.

Once the transfer phase is completed, the spacecraft performs the orbit insertion manoeuvre required to reach the selected halo orbit around the Sun–Earth L1 point. Following orbit acquisition, the deployment sequence is initiated. The boom-driven deployment mechanism progressively extends the four TRAC composite booms while simultaneously unfolding the reflective membrane until the nominal deployed configuration is achieved. Throughout this operation, continuous attitude control is maintained to minimize structural oscillations and ensure a stable membrane deployment.

After deployment, a commissioning phase is carried out to verify the correct functionality of all spacecraft subsystems. Telemetry data are analysed to confirm the successful deployment of the reflector, the structural integrity of the membrane, and the proper operation of the attitude determination and control system. Minor orbit correction manoeuvres may also be performed to refine the operational orbit and optimize the orientation of the reflector with respect to the Sun.

The nominal operational phase represents the longest portion of the mission lifetime. During this period, the deployed membrane continuously reflects a small fraction of the incoming solar radiation away from the Earth while the spacecraft maintains the required orientation through its three-axis attitude control system. Periodic station-keeping manoeuvres compensate for orbital perturbations generated by gravitational forces and Solar Radiation Pressure (SRP), ensuring that the spacecraft remains within the desired operational region around the Sun–Earth L1 point.

The modular nature of the proposed architecture allows multiple spacecraft to operate simultaneously as part of a distributed constellation. Since each spacecraft functions as an independent unit, individual failures do not compromise the overall mission effectiveness. Additional spacecraft can be launched during the mission lifetime to increase the total reflective area or replace failed units, thereby enhancing the long-term robustness and scalability of the system.

At the end of the operational lifetime, the spacecraft enters the disposal phase. Depending on the remaining propellant and the adopted mission policy, the spacecraft may be transferred to a disposal trajectory away from the operational region or passivated to minimize the risk of generating additional space debris. Since the operational environment is located in deep space rather than in Earth orbit, disposal activities primarily aim to prevent interference with future missions operating near the Sun–Earth L1 point.

The principal operational phases of the mission are summarized in Table 5.4.

Mission Phase	Primary Activities
Launch	Launch vehicle ascent, spacecraft separation, initial stabilization.
Transfer	Interplanetary transfer toward the Sun–Earth L1 region and sub-system checkout.
Orbit Insertion	Halo orbit acquisition and trajectory correction manoeuvres.
Deployment	Extension of the TRAC booms and deployment of the reflective membrane.
Commissioning	Verification of subsystem functionality and deployment success.
Nominal Operations	Solar radiation reflection, attitude control, station-keeping, telemetry, and health monitoring.
End-of-Life	Spacecraft passivation or disposal trajectory following mission completion.

Table 5.4: Summary of the mission operational phases.

The operational concept presented in this section completes the preliminary definition of the proposed SB-SRM mission. Together with the mission architecture and the spacecraft configuration discussed in the previous sections, it establishes a coherent engineering framework that can support future developments, including detailed subsystem design, trajectory optimization, structural verification, and mission performance assessment.

5.6 Preliminary design Summary

This chapter presented the preliminary mission design of the proposed Space-Based Solar Radiation Management (SB-SRM) mission based on a constellation of Deployable Reflective Membrane Arrays (DRMAs). Building upon the technology selection performed in Chapter 3 and the mission concept trade-off carried out in Chapter 4, a coherent baseline mission architecture was defined.

The mission overview introduced the principal characteristics of the proposed concept, including its scientific objective, operational orbit, distributed architecture, and modular philosophy. Subsequently, the overall mission architecture was described by identifying the interaction between the launch, space, ground, and operations segments required to accomplish the mission objectives.

A preliminary spacecraft configuration was then established by integrating mature deployable membrane technologies with conventional spacecraft subsystems. The selected configuration adopts a lightweight aluminized Kapton membrane supported by four TRAC composite booms and deployed through a boom-driven mechanism. The spacecraft is assumed to operate as a three-axis stabilized platform capable of maintaining the required reflector orientation throughout the mission lifetime.

Finally, the operational concept of the mission was presented, describing the complete mission lifecycle from launch and transfer to the Sun–Earth L1 halo orbit, through membrane deployment, commissioning, nominal operations, and end-of-life disposal. The proposed operational sequence demonstrates the feasibility of implementing the selected mission concept using technologies that are either currently available or under active development.

Overall, the preliminary mission design confirms the technical coherence of the proposed SB-SRM architecture. By combining a distributed constellation of deployable membrane spacecraft with mature structural technologies and a modular mission philosophy, the proposed concept provides a realistic engineering baseline for future investigations aimed at increasing the Technology Readiness Level of large-scale space-based climate mitigation systems.

Although the present work is limited to a preliminary conceptual design, it establishes a complete systems engineering framework that can support subsequent developments, including detailed subsystem sizing, structural optimization, deployment simulations, thermo-mechanical analyses, trajectory optimization, and mission performance assessment.

Conclusions and Future Work

6.1 Conclusions

The increasing urgency of climate change mitigation has stimulated growing interest in innovative technologies capable of complementing conventional greenhouse gas emission reduction strategies. Among the various approaches currently under investigation, Space-Based Solar Radiation Management (SB-SRM) has emerged as a promising long-term solution capable of reducing the amount of incoming solar radiation reaching the Earth through the deployment of large reflective structures in space. Although the concept remains at an early stage of technological development, recent advances in lightweight deployable space structures have significantly improved the feasibility of membrane-based reflector systems, motivating further engineering investigations.

The primary objective of this thesis was to perform a comprehensive preliminary engineering assessment of Deployable Membrane Reflectors (DMRs) for potential SB-SRM applications. Rather than focusing on a single technological aspect, the work adopted a systems engineering approach encompassing the analysis of deployable membrane technologies, structural configurations, deployment mechanisms, mission architectures, and preliminary mission design. This multidisciplinary perspective enabled the identification of a coherent baseline solution that integrates mature deployable structure technologies with a distributed mission architecture suitable for future large-scale climate mitigation applications.

A comprehensive review of the current state of the art highlighted the rapid evolution of deployable membrane technologies over the last two decades. Flight demonstrations conducted through missions such as IKAROS, NanoSail-D, LightSail 2 and ACS3 have progressively increased the Technology Readiness Level of lightweight membrane spacecraft, providing valuable heritage for future large deployable reflector systems. Building upon this technological background, the structural trade-off performed in this work identified the combination of an aluminized Kapton membrane, four Tape-Rolled Assembled Composite (TRAC) booms, and a boom-driven deployment mechanism as the most suitable structural configuration for the proposed mission.

The subsequent mission concept trade-off compared several Space-Based Solar Radiation Management architectures, including monolithic space shields, distributed optical systems, particulate solar shields, and Deployable Reflective Membrane Arrays. The analysis demonstrated that a distributed constellation of deployable membrane spacecraft provides the most balanced compromise between mission effectiveness, scalability, technological maturity, deployment feasibility, and operational robustness. Based on these results, a preliminary mission architecture operating in a Sun–Earth L1 halo orbit was proposed and further refined through the definition of the spacecraft configuration and the associated operational concept.

Overall, the results obtained throughout this thesis demonstrate that Deployable Reflective Membrane Arrays represent a technically credible and scalable approach for future Space-Based Solar Radiation Management missions. Although considerable technological and programmatic challenges remain before operational implementation becomes feasible, the proposed architecture is founded upon technologies that have already accumulated significant flight heritage and therefore offers a realistic baseline for future engineering developments.

In conclusion, this work contributes to the ongoing research on large deployable space structures by providing an integrated preliminary mission design framework that combines structural technology selection with mission-level systems engineering. The proposed methodology may serve as a starting point for future studies aimed at the detailed design, optimization, and experimental validation of deployable membrane reflector systems for space-based climate mitigation applications.

6.2 Main Contributions

The research activities presented in this thesis resulted in the definition of a preliminary engineering framework for the application of Deployable Membrane Reflectors (DMRs) to Space-Based Solar Radiation Management (SB-SRM). The principal contributions of this work can be summarized as follows:

- A comprehensive review of the current state of the art of Space-Based Solar Radiation Management was carried out, identifying the principal engineering approaches proposed in the literature together with their respective advantages, limitations, and technological maturity.
- An extensive survey of Deployable Membrane Reflector technologies was performed, including membrane materials, boom architectures, deployment mechanisms, structural configurations, and the most significant flight demonstrations achieved through missions such as IKAROS, NanoSail-D, LightSail 2, and ACS3.
- A structured technology trade-off analysis was conducted to identify the most suitable structural solution for the proposed reflector system. The analysis led to the selection of an aluminized Kapton membrane supported by four Tape-Rolled Assembled Composite (TRAC) booms deployed through a boom-driven mechanism.
- Several candidate Space-Based Solar Radiation Management mission concepts were comparatively assessed using a systems engineering approach. Monolithic space shields, distributed optical systems, particulate solar shields, and Deployable Reflective Membrane Arrays were evaluated according to mission effectiveness, scalability, technology readiness, deployment feasibility, operational robustness, manufacturability, and cost effectiveness.
- A preliminary mission concept based on a distributed constellation of Deployable Reflective Membrane Arrays operating in a Sun–Earth L1 halo orbit was proposed and justified through a quantitative trade-off analysis.
- A preliminary mission architecture was developed, including the definition of the mission segments, spacecraft configuration, operational concept, and high-level mission requirements required to support future engineering developments.
- Finally, the work established a coherent systems engineering methodology linking structural technology selection, mission concept evaluation, and preliminary mission design within a unified design framework applicable to future Space-Based Solar Radiation Management studies.

Overall, the contributions presented in this thesis provide a technically consistent baseline for future investigations on deployable membrane reflector systems, supporting the transition from conceptual studies toward more detailed engineering analyses and experimental validation.

6.3 Limitations of the Present Work

Although the results presented in this thesis demonstrate the feasibility of employing Deployable Reflective Membrane Arrays (DRMAs) as a potential architecture for future Space-Based Solar Radiation Management (SB-SRM) missions, the present work intentionally remains at the level of a preliminary conceptual design. Consequently, several assumptions and simplifications were introduced in order to maintain the scope of the study within the objectives of a Phase A mission assessment.

The first limitation concerns the level of structural modelling adopted throughout the analysis. The structural configuration of the deployable reflector was selected through a technology trade-off based on available literature and demonstrated flight heritage, without performing detailed finite element analyses or nonlinear structural simulations. In particular, complex phenomena such as membrane wrinkling, thermoelectric deformations, boom buckling, and dynamic deployment behaviour were discussed qualitatively but were not investigated through high-fidelity numerical models.

Similarly, the mission analysis was intentionally limited to the conceptual level. Although the Sun–Earth L1 halo orbit was identified as the preferred operational environment, no detailed trajectory optimization, orbit propagation, or station-keeping analysis was carried out. The effects of Solar Radiation Pressure, gravitational perturbations, and long-term orbital stability were considered only from a qualitative systems engineering perspective.

Another important simplification concerns the spacecraft design. The preliminary configuration proposed in Chapter 5 identifies the principal spacecraft subsystems and their functional interactions without performing detailed engineering sizing. Consequently, subsystem mass budgets, power budgets, communication link analyses, thermal control sizing, propulsion requirements, and attitude control performance remain outside the scope of the present work.

Furthermore, the performance of the proposed Space-Based Solar Radiation Management system was not evaluated through climate or radiative transfer simulations. The analysis assumes that the deployable membrane constellation provides the required reflective functionality, while the quantitative assessment of its global climatic impact requires multidisciplinary studies involving atmospheric physics, Earth system modelling, and long-term climate simulations.

Finally, the proposed mission architecture assumes the availability of future launch capabilities capable of deploying large constellations of deployable membrane spacecraft. Although recent advances in reusable launch systems and lightweight space structures suggest that such architectures may become increasingly feasible, the economic and programmatic aspects associated with the deployment of large-scale SB-SRM infrastructures were not addressed in this thesis.

Despite these limitations, the adopted methodology remains fully consistent with the objectives of a preliminary engineering feasibility study. Rather than providing a complete spacecraft design, this work establishes a coherent systems engineering framework that links technology assessment, mission concept selection, and preliminary mission definition. As such, it provides a solid foundation upon which more detailed analyses and future engineering developments can be built.

Bibliography

- [1] James T Early. “Space-based solar shield to offset greenhouse effect”. In: *Journal of the British Interplanetary Society* 42 (1989), pp. 567–569.
- [2] Robert M Zubrin and Dana G Andrews. “Magnetic sails and interplanetary travel”. In: *Journal of Spacecraft and Rockets* 28.2 (1991), pp. 197–203.
- [3] P Fanning and L Hollaway. “The deployment analysis of a large space antenna”. In: *International Journal of Space Structures* 8.3 (1993), pp. 209–220.
- [4] RE Freeland and G Bilyeu. “In-step inflatable antenna experiment”. In: *Acta Astronautica* 30 (1993), pp. 29–40.
- [5] Gerard Gómez, Josep Masdemont, and Carles Simó. “Quasihalo orbits associated with libration points”. In: *The Journal of the Astronautical Sciences* 46.2 (1998), pp. 135–176.
- [6] Colin R McInnes. “Solar sail mission applications for non-Keplerian orbits”. In: *Acta Astronautica* 45.4-9 (1999), pp. 567–575.
- [7] Mark W Thomson. “The AstroMesh deployable reflector”. In: *IEEE Antennas and Propagation Society International Symposium. 1999 Digest. Held in conjunction with: USNC/URSI National Radio Science Meeting (Cat. No. 99CH37010)*. Vol. 3. IEEE. 1999, pp. 1516–1519.
- [8] L Rozelle et al. “Phase inversion membranes”. In: *Encyclopedia of separation science* (2000), pp. 3331–3346.
- [9] Christopher HM Jenkins. *Gossamer spacecraft: membrane and inflatable structures technology for space applications*. American Institute of Aeronautics and Astronautics, 2001.
- [10] CH Jenkins and WW Schur. “Gore/seam architectures for gossamer structures”. In: *Journal of spacecraft and rockets* 39.5 (2002), pp. 669–673.
- [11] I Funaki et al. “Study of a plasma sail for future deep space missions”. In: *28th International Electric Propulsion Conference, Toulouse, France*. 2003, pp. 2003–89.
- [12] David Cadogan et al. “Morphing inflatable wing development for compact package unmanned aerial vehicles”. In: *45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference*. 2004, p. 1807.
- [13] Pekka Janhunen. “Electric sail for spacecraft propulsion”. In: *Journal of Propulsion and Power* 20.4 (2004), pp. 763–764.
- [14] Roger Angel. “Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1)”. In: *Proceedings of the National Academy of Sciences* 103.46 (2006), pp. 17184–17189.
- [15] Michel Denis et al. “Deployment of the MARSIS radar antennas on-board Mars express”. In: *SpaceOps 2006 Conference*. 2006, p. 5959.
- [16] Malcolm Macdonald et al. “GeoSail: an elegant solar sail demonstration mission”. In: *Journal of Spacecraft and Rockets* 44.4 (2007), pp. 784–796.
- [17] Thomas Murphey. “Historical perspectives on the development of deployable reflectors”. In: *50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference 17th AIAA/ASME/AHS Adaptive Structures Conference 11th AIAA No.* 2009, p. 2605.

- [18] Kevin E Trenberth, John T Fasullo, and Jeffrey Kiehl. "Earth's global energy budget". In: *Bulletin of the american meteorological society* 90.3 (2009), pp. 311–324.
- [19] Shahid Baig and Colin R McInnes. "Light-levitated geostationary cylindrical orbits are feasible". In: *Journal of Guidance, Control, and Dynamics* 33.3 (2010), pp. 782–793.
- [20] Pekka Janhunen et al. "Invited Article: Electric solar wind sail: Toward test missions". In: *Review of scientific instruments* 81.11 (2010).
- [21] Peter Fortescue, Graham Swinerd, and John Stark. *Spacecraft systems engineering*. John Wiley & Sons, 2011.
- [22] Les Johnson et al. "NanoSail-D: A solar sail demonstration mission". In: *Acta astronautica* 68.5-6 (2011), pp. 571–575.
- [23] P Alan Jones and Brian R Spence. "Spacecraft solar array technology trends". In: *IEEE Aerospace and Electronic Systems Magazine* 26.8 (2011), pp. 17–28.
- [24] David W. Keith. *A Case for Climate Engineering*. MIT Press, 2013.
- [25] AE Andrews et al. "CO₂, CO, and CH₄ measurements from tall towers in the NOAA Earth System Research Laboratory's Global Greenhouse Gas Reference Network: Instrumentation, uncertainty analysis, and recommendations for future high-accuracy greenhouse gas monitoring efforts". In: *Atmospheric Measurement Techniques* 7.2 (2014), pp. 647–687.
- [26] Amir S Gohardani. "A Historical Glance at Solar Sails". In: *AIAA SPACE 2014 Conference and Exposition*. 2014, p. 4181.
- [27] Osamu Mori et al. "Overview of IKAROS mission". In: *Advances in solar sailing* (2014), pp. 25–43.
- [28] Malcolm Macdonald et al. "Concept-of-operations disposal analysis of spacecraft by gossamer structure". In: *Journal of Spacecraft and Rockets* 52.2 (2015), pp. 517–525.
- [29] Manan Arya, Nicolas Lee, and Sergio Pellegrino. "Ultralight structures for space solar power satellites". In: *3rd AIAA Spacecraft Structures Conference*. 2016, p. 1950.
- [30] Bo Fu, Evan Sperber, and Fidelis Eke. "Solar sail technology—A state of the art review". In: *Progress in Aerospace Sciences* 86 (2016), pp. 1–19.
- [31] M. Bessa and Sergio Pellegrino. "Design of ultra-thin composite deployable shell structures through machine learning". In: Sept. 2017.
- [32] Juan M Fernandez. "Advanced deployable shell-based composite booms for small satellite structural applications including solar sails". In: *International symposium on solar sailing 2017*. NF1676L-25486. 2017.
- [33] Harijono Djojodihardjo. "Review of solar magnetic sailing configurations for space travel". In: *Advances in Astronautics Science and Technology* 1.2 (2018), pp. 207–219.
- [34] Kevin LG Parkin. "The breakthrough starshot system model". In: *Acta astronautica* 152 (2018), pp. 370–384.
- [35] Tom Sprowitz et al. "Membrane deployment technology development at DLR for solar sails and large-scale photovoltaics". In: *2019 IEEE Aerospace Conference*. IEEE. 2019, pp. 1–20.
- [36] Craig Underwood et al. "InflateSail de-orbit flight demonstration results and follow-on drag-sail applications". In: *Acta Astronautica* 162 (2019), pp. 344–358.
- [37] Dawn M McIntosh, John D Baker, and Joseph A Matus. "The nasa cubesat missions flying on artemis-1". In: (2020).
- [38] Masanori Matsushita et al. "Solar power sail membrane prototype for OKEANOS mission". In: *Advances in Space Research* 67.9 (2021), pp. 2899–2911.
- [39] David A Spencer et al. "The LightSail 2 solar sailing technology demonstration". In: *Advances in Space Research* 67.9 (2021), pp. 2878–2889.
- [40] William K Wilkie. "Overview of the nasa advanced composite solar sail system (acs3) technology demonstration project". In: *AIAA scitech 2021 forum*. 2021, p. 1260.

- [41] Les Johnson et al. “The nasa solar cruiser mission-solar sail propulsion enabling heliophysics missions”. In: (2022).
- [42] Benjamin C Bromley, Sameer H Khan, and Scott J Kenyon. “Dust as a solar shield”. In: *PLOS Climate* 2.2 (2023), e0000133.
- [43] Jonathan P Gardner et al. “The James Webb space telescope mission”. In: *Publications of the Astronomical Society of the Pacific* 135.1048 (2023), p. 068001.
- [44] Intergovernmental Panel on Climate Change. *Climate Change 2023: Synthesis Report*. 2023.
- [45] Elena Ancona and Roman Ya Kezerashvili. “Recent advances in space sailing missions and technology: review of the 6th International Symposium on Space Sailing (ISSS 2023)”. In: *arXiv preprint arXiv:2411.12492* (2024).
- [46] Maximilien Berthet et al. “Space sails for achieving major space exploration goals: Historical review and future outlook”. In: *Progress in Aerospace Sciences* 150 (2024), p. 101047.
- [47] Joel Eldo and Efstratios L Ntantis. “Review of lagrangian points and scope of stationary satellites”. In: *Proceedings of the 8th International Conference on Research, Technology, and Education of Space, H-Space*. 2024, pp. 25–26.
- [48] S Pete Worden et al. “Breakthrough Starshot program overview”. In: *Laser Propulsion in Space* (2024), pp. 39–70.
- [49] Ruonan Zhang et al. “Overview and key technology of the membrane drag sail for low Earth orbit satellite deorbit”. In: *Space: Science & Technology* 4 (2024), p. 0115.