A Roadmap Toward a Planetary Sunshade for Space-Based Solar Geoengineering

IAC-24,D4,1,4,x83276

A Roadmap toward a Planetary Sunshade for Space-based Solar Geoengineering

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Abstract

The objective of this paper is to present a roadmap for the technology development toward a Planetary Sunshade System, a space-based solar geoengineering project aimed at reversible solar radiation modification to mitigate global warming. Earth's climate change is mostly due to the increasing concentration of greenhouse gases in the atmosphere, which leads to a general rise of the temperatures. A space-based geoengineering infrastructure has been previously proposed to reduce the oncoming solar irradiance, by placing a 'solar light umbrella', called Planetary Sunshade System, between the Sun and the Earth. To address the full development of a Planetary Sunshade System, a technology roadmap is needed which considers a step-by-step high-level plan of technology development, mission planning, launch preparation, international cooperation, highlighting the multi-phase development strategy from initial design to final deployment. First, the roadmap phases for production and deployment are outlined in chronological order. The analysis of technology development begins with the current technology readiness level, encompassing system design and factors such as mass, dimensions, area, and the total number of solar-sail satellites. Logistic aspects, including in-space assembly of the fully deployed system, are also examined. Finally, launch preparation is discussed encompassing heavy launcher design, facilities, production and launch sites. The proposed roadmap not only provides a starting point for the design and development of the Planetary Sunshade System but also a critical tool for evaluating the feasibility of direct climate action from space. Through this paper, we aim to establish the groundwork for a future Planetary Sunshade endeavour, and to contribute to the broader discussion on space-based climate action.

Keywords: Planetary Sunshade, Space-based Geoengineering, Climate Change Mitigation, Roadmap, Technology Development, In-Space Assembly, Orbital Robotics

1. Introduction

Climate change is one of the most pressing challenges of our time, driven primarily by the increasing concentration of greenhouse gases in the atmosphere [1]. The rising levels of greenhouse gases in our atmosphere, primarily caused by human activities such as burning fossil fuels, deforestation, and industrial processes, have resulted in significant global temperature increases. Addressing climate change necessitates the exploration of various mitigation strategies, including cutting greenhouse gas emissions and implementing adaptation measures to manage unavoidable impacts [2]. However, these efforts alone may not be sufficient to avert the most severe outcomes of global warming. This realization has led the scientific community to explore more innovative and potentially transformative approaches, such as solar geoengineering [3].

Developing a Planetary Sunshade System (PSS) is a substantial technological and logistical challenge, requiring advancements in space engineering, international cooperation, and environmental assessment. This paper outlines a comprehensive roadmap for the PSS's technology development, detailing the steps from initial design to final deployment. By establishing this roadmap, we aim to provide a structured plan for evaluating the feasibility and potential benefits of this innovative climate intervention, thus contributing to the broader discussion on effective and sustainable climate action.

The paper is organized as follows: Sec. 2 presents an overview on geoengineering and sunshades. Sec. 3 explains the fundamental astrodynamics guiding the optimal design of a PSS. Sec. 4 discusses technologies for implementing a PSS. In Sec. 5 the Roadmap is presented. Sec. 6 discusses the risks and cost associated with the PSS. Sec. 7 highlights political challenges, while Sec. 8 summarizes the paper and its main contributions.

2. Background

2.1 Geoengineering

If global temperatures threaten to exceed acceptable limits, geoengineering might become a necessary solution for global welfare [4]. Geoengineering encompasses two main categories: solar radiation management (SRM) and carbon dioxide removal (CDR).

CDR focuses on reducing atmospheric CO_2 through methods such as afforestation, bioenergy with carbon capture and storage (BECCS), and direct air capture (DAC) [5, 6]. While DAC is theoretically ideal due to its direct approach, it is energy-intensive and must rely on fossil-free energy sources, making it less feasible in the near future [4].

SRM involves two primary techniques. The first aims to reflect a small percentage of the Sun's energy back into space using methods like stratospheric aerosol injection (SAI) or cloud brightening [7]. SAI, which involves injecting aerosols into the stratosphere to reflect sunlight, is likely the less expensive method in the short term. However, it requires continuous replenishment for a decade to century long periods since aerosols remain aloft for a much shorter period compared to the centuries-long presence of CO_2 in the atmosphere [8]. Furthermore, the potential side effects of SAI, such as changes in weather patterns and impacts on the ozone layer, also pose significant risks.

The second SRM method involves reducing solar radiation with materials placed in space. This geoengineering solution bridges the domains of climate mitigation and space engineering, requiring a specific architectural framework [9]. This space-based geoengineering solution, while likely more expensive, could potentially have fewer side effects, and top-level comparisons w.r.t. atmospheric strategies have been detailed [10]. Our proposal is to deploy a *Planetary Sunshade System* —a set of membranes positioned between the Sun and Earth. These membranes could be controlled from Earth and quickly rotated to cease the shading effect if necessary. The optimal position for the sunshade from several aspects is beyond Lagrange point L_1 in the Sun–Earth system, ca 2.4 million km away from Earth [11]. In principle, one could consider the membranes to be in orbit around Earth [12], as satellites, however this is less efficient [13].

2.2 The Planetary Sunshade System

The PSS is a space-based reversible solar geoengineering infrastructure proposed to reduce the oncoming solar radiance by setting a 'solar-light umbrella'

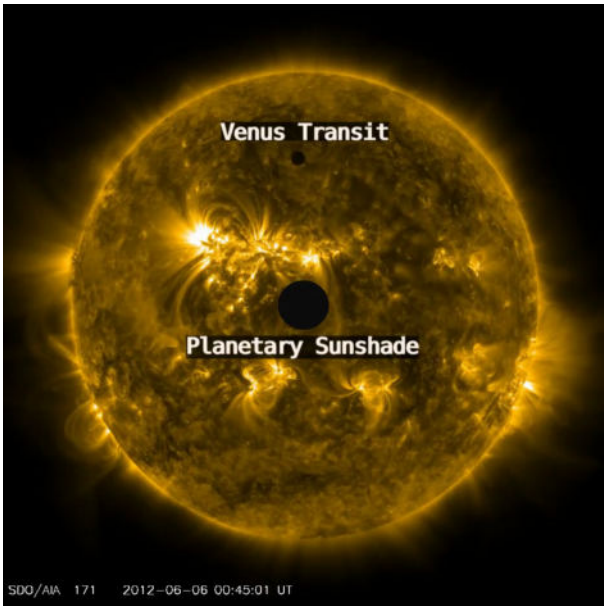

Figure 1: *Conceptual visualization of space-based climate change mitigation strategy represented by a planetary sunshade system,compared with a Venus transit as seen from Earth on 06/06/2012, source [14].*

between the Sun and Earth. Fig. 1 shows a PSS composed by a swarm of solar-sail satellites assembled in space. The concept of the planetary sunshade originates with Konstantin Ėduardovič Ciolkovskij, who, in 1893, discussed the use of space mirrors to reflect solar light [15]. However, it was Hermann Oberth who first explicitly analyzed, in terms of orbital dynamics and structure, the idea of using a reflector to illuminate a part of the Earth [16]. In 1979, the concept of weather stabilization emerged, [17] and the reflector idea later evolved a shield to combat climate change. In 1989 James T. Early proposed a 2,000 km-wide glass shield at the Sun-Earth first Lagrange point L1, to counteract the greenhouse effect on Earth [18]. The first (to the authors´ knowledge) to propose a solution with Earth-manufactured shades, was Roger Angel in 2006 [19]. He suggested trillions of flying small space robots, weighing 1 gram each, which would be launched with a gigantic electromagnetic gun embedded in a mountain.

Generally, the main strategy consists of a swarm of solar-sail satellites, capable of active control, which are assembled to build a single occulting disk at a constant [20, 21] or variable [22, 23] distance from Earth, these two modalities are respectively named static and dynamic sunshades. The astrodynamics and climate output, specifically of a dynamic single sunshade, has been investigated in [22, 23]. Another strategy is to consider a swarm of orbiting solar sail satellites which act as a sunshade [24, 25, 26, 27]. Finally, other architectures have been proposed utilizing space resources [28, 29], including the Moon [30], such as diffuse and passively controlled dust clouds [31] and foil sunshades [32, 33].

The reason for considering space resources lies on the very large cost to launch from Earth millions of tons needed for a sufficiently large shade, or systems of smaller shades. However, recent developments in new rockets, in particular by Space-X with the coming Starship-Superheavy rocket, are drastically changing the space accessibility. The "rule of thumb", until about 20 years ago, used to be that the price to send one kg to space was $10,000. It has already fallen by almost an order of magnitude and is expected to fall by at least one more [34]. It is now realistic to consider a Planetary Sunshade that is manufactured on Earth [24].

With current climatological trends, it might be necessary to start implementing a Planetary Sunshade already in the 2040's. By then, some critical in-space manufacturing technologies may not be at a high Technological Readiness Level (TRL). Therefore, we assume that the planetary sunshade Roadmap will consider on-Earth production of its modules. The total size of the planetary sunshade would depend on the mitigation scenario chosen, such as how much cooling would be needed and shall some latitude variation be implemented. Typically, assumptions vary between 0.5% and 2% shading, much based on a study claiming that a global solar radiance reduction of about 1.7% would be needed to mitigate the effects of doubling the carbon dioxide concentration in the atmosphere [35]. The total area of such a system, placed in the vicinity of photogravitational L_1, is about $1e+8$ [km^2]. The mass would be in the order of $1e+8$ to $1e+12$ [kg], mainly depending on the optical properties of the membrane, as detailed in Section 3.1.1.

Among the phases of the sunshade programme, the following is considered:

1. Development and manufacturing of the Sunshade (including transfer capabilities). A mem-

brane will be selected and developed. Its optical properties will drive the total mass of the whole system, together with the deployment mechanism and structure for these large areas. These can include some assembly mechanisms and capabilities.

2. Launch to space (probably to Earth orbit), which can be assumed to be the main cost driver.
3. Transfer of sunshades from Earth orbit to the final position, for example, by solar sailing or electric propulsion, or a combination thereof.
4. Station keeping and operation & coordination at the final position. These can include assembly and formation flight maneuvers.

Since there probably will be thousands or even millions of individual sunshade spacecraft, swarm control for formation flying is necessary. Optimal orbit for climate mitigation should also be implemented [25, 27, 23, 22]. Among other developments, it might be necessary to add relays spacecraft outside the Sun-Earth line for communication due to massive radio noise in the Sun-Earth direction, where the shade system is [36].

The Roadmap to a Planetary Sunshade should include the steps of how to study and optimize these phases and consider the implications and consequences. Development with tests, including in-orbit precursors, should be done as soon as possible in order to have a ready design for a whole system that could be implemented from 2040, if necessary.

3. Fundamental Astrodynamics for a Sunshade System

3.1 Basic Definitions

A planetary sunshade is a space-based system for achieving solar geoengineering. We begin by presenting the procedure in [26] which analyzes a planetary sunshade system that is made up of a single very-large surface, likely resulting from the on-orbit assembly of a multitude of modular satellites. Each satellite composing the sunshade is assumed to have a large planar shading surface, that we call a solar-sail.

The photo-gravitational Circular Restricted Three Body Problem (CR3BP) is used in this work as a model to investigate the dynamics of a planetary sunshade system. In particular, the two primaries are two point masses representing the Sun's and the Earth's center of mass (CoM), considering a constant distance between them equal to 1 astronomical unit (AU). The two primaries perform circular orbits about their common CoM [37]. In our work, the values of primaries' masses, relative distance and period, are adopted as per [38]. These quantities are used to make the photo-gravitational CR3BP equations non-dimensional. In this model, a solar-sail satellite is attracted to each of the primaries, and is affected by the Solar Radiation Pressure effect (SRP). The SRP is the force produced by sunlight photons impinging on the surface of the satellite, and whose direction can be modelled parallel to the solar-sail surface normal $\hat{\boldsymbol{n}}$ [39].

In order to discuss the system dynamics, it is useful to consider a barycentric and synodic (or co-rotating) Cartesian Coordinate System (CCS), defined as follows. Its origin O_{xyz} is located at the CoM of the Sun–Earth system, which is fixed in an inertial frame; its $\hat{\boldsymbol{x}}$ axis is the straight line joining the Sun's to Earth's center; its $\hat{\boldsymbol{z}}$ axis is along the angular momentum vector of the Sun–Earth system; finally, its $\hat{\boldsymbol{y}}$ axis completes a right-hand CCS. The Sun's and Earth's CoM are fixed in this CCS, and located along the $\hat{\boldsymbol{x}}$ axis, with a distance from the CoM d_{SCoM} and d_{CoME} equal in module to μ and $1-\mu$, respectively. μ is defined as the mass parameter, where $\mu = \frac{m_e}{m_s+m_e}$ with m_s and m_e respectively equal to Sun's and Earth's mass.

3.1.1 Mass and Position Optimization

One of the crucial challenges of the planetary sunshade is to optimize its space system mass according to its location, in order to accomplish a desired solar radiance reduction. The main constraint is that the sunshade must be inside the shadow cone created by the sunshade, either (partially) inside the umbra, penumbra or antumbra zone. In order to achieve this condition, the sunshade CoM must be close to $\hat{\boldsymbol{x}}$ axis.

Generally, for the classic CR3BP case, a gravitational equilibrium point exists on the plane of motion, between the Sun and the Earth, along $\hat{\boldsymbol{x}}$: it is called the first Lagrangian point (L_1). The L_1 point is located at a distance from Earth $d_{L_1E} = 1.4959e+6$ [km]. If the SRP is added to the model, and the normal to the sail is parallel to $\hat{\boldsymbol{x}}$, the equilibrium point is along that same line, but closer to the Sun: it is called here the photo-gravitational first Lagrangian point (L_1^*). This equilibrium point is the chosen one for the sunshade, since it is located on $\hat{\boldsymbol{x}}$, between Sun and Earth, and the shading is maximized since the sunshade surface is orthogonal to $\hat{\boldsymbol{x}}$.

In particular, by following the procedure in [32], the optimal position of the equilibrium point of the rotating system, is calculated from the balance of accelerations due to the Sun and Earth gravitational forces $a_{g_S}+a_{g_E}$, centrifugal force a_c, and SRP a_{SRP} as in (1):

$$\begin{aligned} &a_{g_S}+a_{g_E}+a_c+a_{SRP}=0,\\ &a_{g_S}=-\frac{1-\mu}{(1-d^*)^2},\\ &a_{g_E}=\frac{\mu}{d^{*2}},\\ &a_c=1-\mu-d^*,\\ &a_{SRP}=\beta\frac{1-\mu}{(1-d^*)^2} \end{aligned} \tag{1}$$

where d^* is the distance of L_1^* from Earth and $\beta=\sigma^*\frac{\mathcal{A}}{M}$ corresponds to the SRP-to-solar gravity ratio, giving its expression as a function of the solar-sail area-to-mass ratio. $\sigma^*\sim 1535\mathcal{Q}$ [kg/km^2] is the solar-sail critical loading parameter, with $\mathcal{Q}$ as the solar-sail optical properties parameter which depends on the solar-sail material, ranging from perfectly reflecting surface with $\mathcal{Q}=1$ to $\mathcal{Q}=0$ with specular reflection.

It is possible to demonstrate that there exists an optimum β, or equivalently distance d^*, that minimizes the total mass of the system which is independent of solar radiance reduction $\frac{\delta Q}{Q}$ needed. From the equilibrium equation in Eq. (1), it yields a relationship between β and d^*:

$$\begin{aligned} \beta(d^*)=&\frac{(1-d^*)^2}{(1-\mu)}\\ &\left(d^*-(1-\mu)+\frac{(1-\mu)}{(1-d^*)^2}-\frac{\mu}{d^{*2}}\right). \end{aligned} \tag{2}$$

Moreover, the sunshade area $\mathcal{A}$ is a function of d^* and $\frac{\delta Q}{Q}$, since $\frac{\delta Q}{Q}$ is calculated as the ratio between the solid angles of the sunshade Ω_D and of the Sun Ω_S , as seen from the Earth, which gives:

$$R(d^*)=R_s\frac{d^*}{d_{SE}}\sqrt{\frac{\delta Q}{Q}},\;\; \mathcal{A}(d^*)=\pi R^2(d^*), \tag{3}$$

with R_S as the Sun Radius and d_{SE} as the distance between the Sun and the Earth. Finally, the sunshade mass M is expressed as:

$$M(d^*)=\sigma^*\frac{\mathcal{A}(d^*)}{\beta(d^*)}=\frac{\frac{\sigma^*\pi R_S^2\frac{\delta Q}{Q}(1-\mu)}{d_{SE}^2}d^{*2}}{(d^*+\mu)^2(-d^*+\frac{(1-\mu)}{(d^*+\mu)^2}-\frac{\mu}{(d^*-(1-\mu))^2})}. \tag{4}$$

The optimal distance is $d^*\sim 2.364e+06$ [km] (with a distance from L_1 associated to pure CR3BP equal to $d_{L_1^*L_1}=8.681e+5$ [km]) and it is independent of $\frac{\delta Q}{Q}$, such as β, while M and R have respectively linear and square root dependency. At this distance, considering $\mathcal{Q}=1$ and $\frac{\delta Q}{Q}=1.7\%$, the value of mass, radius and beta are respectively equal to $M=2.847e+11$ [kg], $R=1.436e+03$ [km] and $\beta=0.0349$. Notably, the minimum Mass M corresponds to a minimal cost that doesn't take in account the orbital transfer, launch and system engineering development cost. A global optimization must take into account those aspects which might result in a different value [26].

Fig. 2 shows a visualization of the planetary sunshade located at optimal L_1^* with the acting forces and the shadow cones produced of umbra, penumbra and antumbra. In this case, the earth would be totally inside the antumbra cone, while the umbra cone terminates at a distance from Earth $d_{UE}=2.053e+6$ [km].

4. Technologies

The development of a Planetary Sunshade System presents significant technological challenges that require coordinated international efforts. This section provides an overview of the main technologies involved we especially consider necessary to develop further for a sunshade system. Further details for

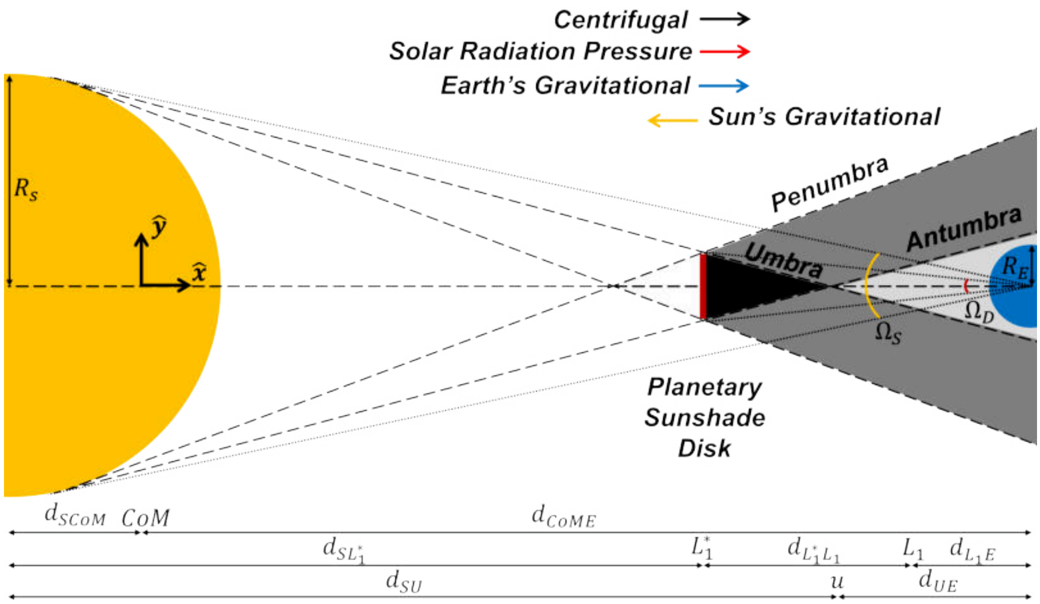

Figure 2: *A planetary sunshade located at L_1^* with the acting forces and the shadow cones produced*

those are discussed in the subsequent sections. Other technologies, including satellite (or spacecraft) buses and launchers, are considered sufficiently general to be readily available when the system is expected to be implemented.

4.1 Solar Sail

Solar sailing is a possible transfer method to transport the sunshade system from Earth to the vicinity of L_1. Similar to how a sailboat is propelled forward by wind, solar sails are propelled forward by sunlight [40]. Solar sails have a few specific design requirements to ensure desired performance. The sail must have at least one highly reflective surface to exchange momentum from the sunlight. To maximize the acceleration, the sail must also be extremely lightweight with a high area-to-mass ratio [39]. This allows the relatively small force exerted by the SRP to have a significant impact on the spacecraft's trajectory over time.

A solar sail typically consists of two primary components: the membrane and coatings on both sides. The membrane forms the base of the sail and provides its structural integrity, while the coatings are applied to achieve the desired surface properties, particularly reflectivity. At least one side of the sail must be coated with a highly reflective material.

In past missions, materials used for the sail membrane have included polyimide resin [41], Clear Polymer 1 (CP1) [42], and Polyethylene Naphthalate (PEN) [43], with thicknesses ranging between $2 - 7.5$ [µm]. According to McInnes [39], aluminum is the optimal material for the reflective coating, due to its high reflectivity, high melting point and low density. A 0.1 [µm] thick aluminum coating will provide a reflectivity Q of about $0.88 - 0.9$. While alternative coatings, such as lithium or silver are possible, they are generally less ideal due to their lower melting point or higher density, respectively.

The durability of a solar sail is dependent on the materials, particularly in terms of resistance to environmental factors encountered in space. Radiation, and in particular ultraviolet (UV) radiation is a significant concern, as it will degrade the sail material over time, leading to a loss of mechanical integrity and reflectivity [44]. The rate and extent of this degradation depend on the material properties and the duration of exposure.

Micrometeoroid impacts pose another challenge. These small, high-velocity particles pose a risk of tearing the sail, which can significantly impair its performance. The sail material must be robust enough to resist such impacts and if tears occur, not let them affect the performance.

The stowability and deployment of the solar sail are influenced by the sail's shape and folding technique. A square-shaped solar sail offers a practical advantage, as it can be divided into four isosceles triangles that are folded and wrapped around spools [45]. This method facilitates compact stowage and simplifies the deployment process, reducing the risk of entanglement or incomplete deployment.

4.2 Deployable Structure and Mechanisms

Deploying large membrane areas to reflect solar radiation is crucial for solar sails. Deployment methods for solar sails are mainly categorized into centrifugal force and deployable booms. IKAROS, the first spacecraft to successfully demonstrate solar sail technology in interplanetary missions, was launched by JAXA in 2010. It uses centrifugal force to deploy a 196 [m^2] membrane at a rotation speed of up to 25 rpm, without any supporting structures. Although spinning solar sails achieve high packing efficiency, their deployment mechanisms are complex and prone to failure. In contrast, three-axis stable solar sails, which utilize lightweight deployable booms, offer high reliability, compact storage, and scalability. These flexible booms can be deployed through various mechanisms, including inflatable deployment, mechanical deployment, and elastic deployment.

One major challenge in scaling up solar sail or sunshade designs is ground testing, necessitating an off-loading system for on-ground kinetic deployment verification. The four-boom sail design is the most common and popular, with significant scale-up potential well-tested on the ground and in space. For example, the Triangle Rollable And Collapsible (TRAC) boom has been successfully used in NanoSail-D, LightSail-1, and LightSail-2. The largest designed four-boom sail, the approximately 1600 [m^2] Solar Cruiser, features nearly 30 [m] long high-strain Composite TRAC booms [46]. NASA's Advanced Composite Solar Sail (ACS3) utilizes a thin-ply spread-tow 7-m rollable composite Collapsible Tubular Mast (CTM) boom. Both TRAC and CTM booms could be viable options for a planetary sunshade.

4.3 Attitude and Orbit Control Systems

Each individual solar sailing satellite will require its own Attitude and Orbit Control System (AOCS) to transfer from Earth to L_1^* and maintain its orbit once there. Several AOCS options are available, however, a combination of systems is typically necessary. One common method is electrical propulsion, using electric thrusters for propulsion and orbit maintenance. This method is well-established, having been used in various space missions, and will therefore not be discussed in detail.

Solar sails present unique AOCS challenges due to their large area and lightweight structure, making them susceptible to oscillations and billowing, which can affect performance. To mitigate these effects, some AOCS systems have been specially developed to apply small, continuous torque rather than large, instantaneous torque.

One system specifically developed for solar sails is the Reflectivity Control Devices (RCDs), thin-film devices incorporated with Polymer Dispersed Liquid Crystal Diodes (PLCDs). The RCDs are mounted on the solar sail's surface and control the reflectivity [47]. They have two modes: ON and OFF, controlled by a voltage input. When voltage is applied, the device is ON and exhibits specular reflection, when it is OFF, it exhibits diffuse reflection [48]. The reflectivity determines the magnitude of the force imparted by Solar Radiation Pressure (SRP), the higher the reflectivity, the greater the force. To maximize torque, the RCDs should be positioned at the sail's edge to achieve the longest possible lever arm. By controlling which RCDs are ON and OFF, the force on the sail can be varied, generating torque in the pitch and/or yaw directions.

RCDs were initially developed to alter the sail's reflectivity and were later adapted for roll control in solar sails [48]. By alternately switching the RCDs ON and OFF and mounting the devices on an angle to the sail, a differential force tangential to the sail plane is created, producing a roll torque near the boom tips. The specific RCDs turned ON/OFF depend on whether a clockwise or counterclockwise torque is desired.

The Active Mass Translator (AMT) was developed to offset the spacecrafts center of mass (CoM) relative to its center of pressure (CoP). The AMT is an inverted translation table with a very low vertical profile, housing motors and transmission components on the sides to maximize internal space [49]. A downside of the design is that the stepper motors must be stacked, limiting their diameter. However, testing has shown that even with their small size, the motors can produce larger torques than required. By combining stepper motors with gearboxes and lead screw drive systems, the AMT can achieve microstepping, enabling very small and precise movements.

The AMT is designed to be placed at the geometric center of the spacecraft, allowing for easy adjustment of the CoM by moving one part of the spacecraft relative to the other. This offset of the CoM relative to the CoP creates control torque. The AMT is capable of providing torque in both pitch and yaw directions.

4.4 Swarm of Solar-Sails

In this section it is highlighted the need to analyze the deliver of a swarm of solar sail satellites for a PSS, considering the architecture presented in [25]

Indeed, to fulfill the planetary sunshade mass/radius requirements described in Sec. 3, since the PSS radius R is in the order of hundreds/thousand of kilometers, due to the constraints of current launch vehicles, it won't be possible to build and launch a single enormous solar-sail, and a multiple of solar-sails, N, have to be deployed either to be assembled or not.

It is possible to adopt one of the following three system architectures, where each solar-sail satellite reduces a fraction $\frac{1}{N}\frac{\delta Q}{Q}$ of required solar radiance reduction:

1. a single solar-sail spacecraft (very likely resulting from the on-orbit assembly of a multitude of modular solar-sail spacecraft);
2. a swarm of multiple ($N \gg 1$) solar-sail spacecraft, each of which in an equilibrium condition, so that the swarm fully covers the same circle of the single solar-sail spacecraft;
3. a swarm of multiple ($N \gg 1$) solar-sail spacecraft, each of which orbiting along a closed orbit, so that the swarm fully covers the same circle of the single solar-sail spacecraft.

The first architecture introduces a range of technological challenges for in-space assembly (ISA), particularly in the construction and maintenance of such large space structures, necessitating the development of robust robotic systems, precise control mechanisms, and advanced maintenance strategies to ensure successful deployment and long-term operation. However, significant progress is being made in the field of ISA, with advancements in autonomous robotic technologies, modular design, and on-orbit manufacturing techniques that will make such complex undertakings more feasible in the future. Additionally, once completed, this architecture won't have the risk of collision between units as seen in the other architectures. Moreover, since L_1^* and the near realms are an unstable, chaotic and perturbed dynamic regime, it is difficult to maintain stable the second architecture, increasing the possibility of collisions and reducing the safety. The third architecture is more efficient and realistic, considering periodic, or quasi-periodic, solar-sail motion around L_1^*. The solar-sails will be distributed along different families of halo orbits achieved through an active control law which exploits the SRP, without the consume of propellant [25]. These orbits are designed to not intersect each other, to avoid possible collisions, and to have minimal variation of the attitude, to maximize the shading. Moreover, an active attitude control in motion give the possibility to handle better the dynamics perturbations.

4.5 Launchers, Launches, and Commissioning

It is important to get a rough understanding of the logistic challenge for launching the PSS. In this section we show approximate numbers for one set of assumptions. The launcher capability is based on the expected performance of the reusable Starship-Super Heavy [50]. Many of the output numbers scales linearly with the inputs of Radianace reduction, Reflectivity and Lead time to full operation. The analysis follows the procedure in [10, 9].

The main driver for the analysis are from mission input, system/design requirements and launcher characteristics.

- Radiance reduction $\frac{\delta Q}{Q}$ [%] [35]
- Reflectivity $\mathcal{Q}$ [-]

- Lead time to full operation T_o [y]
- Area of a single solar-sail satellite A_{ss} [km^2]
- Payload of a single launcher to LEO m_u [ton]
- Maximum daily number of launches per launchpad N_{lp} [1/d], considering an average time for setting and launching
- Reusability of spaceship, booster and tanker N_s^r, N_b^r, N_t^r [-]

The main considerations obtainable from this analysis are:

- Total mass M [ton] to be delivered
- Total area A [km^2] to be covered,
- Total number of solar-sail spacecraft N_{ss} [-]
- Single solar-sail spacecraft mass m_{ss} [ton]
- Number of solar-sail spacecraft per launch N_{ss}^l [1/l], without considering the volume occupied
- Solar-sail spacecraft areal density d_{ss} [ton/km^2]
- Total number of spaceships, boosters and tankers N_s^l, N_b^l, N_t^l [-] launches
- Total number of spaceships boosters and tankers N_s^p, N_b^p, N_t^p [-]to be produced
- Daily number of launches N_l [1/d]
- Total number of launch sites N_{ls} [-]

Tab. 1 outlines an example of this analysis, including the input and output order of magnitude values described above. In order to launch roughly 70 million solar sail spacecraft, they are needed tens of thousands of units for spaceships, boosters and tankers, with hundreds of launches per day from tens of launch sites.

5. Roadmap toward a Planetary Sunshade

Developing a comprehensive roadmap for a project as ambitious as a Planetary Sunshade requires a detailed long-term plan that addresses not only technological advancements but also financial, political, and logistical challenges. Although technological aspects are relatively straightforward with no clear show-stoppers, the most significant challenges lie in overcoming financial and political obstacles. This section will primarily focus on the technological roadmap, recognizing that these other factors are critical but beyond the scope of this discussion.

Table 1: *PSS launchers and launches analysis.*

Input	Value	Unit	Output	Value	Unit
$\frac{\delta Q}{Q}$	1.7	[%]	M	5e+7	[ton]
$\mathcal{Q}$	0.17	[-]	A	6e+6	[km^2]
T_o	40	[y]	N_{ss}	7e+7	[-]
A_{ss}	0.1	[km^2]	m_{ss}	7e-1	[ton]
m_u	150	[ton]	N_{ss}^l	1e+3	[1/l]
N_{lp}	4	[1/d]	d_{ss}	7	[ton/km^2]
N_s^r	12	[-]	N_s^l	3e+5	[-]
N_b^r	1000	[-]	N_b^l	3e+6	[-]
N_t^r	100	[-]	N_t^l	2e+6	[-]
			N_b^p	3e+3	[-]
			N_t^p	2e+4	[-]
			N_l	2e+2	[-]
			N_{ls}	4e+1	[1/d]

The roadmap for the Planetary Sunshade should be structured around a few key milestones:

Technology development by 2040 Ensuring the capability to start operations of the planetary sunshade programme and its first stages.

Full deployment by 2070 Establishing a timeline for achieving a fully operational Planetary Sunshade fulfilling all the programme's goals.

Outcomes beyond Definition of the technological and political achievements, including the necessary agreements.

5.1 Immediate Technological Steps

To achieve operations by 2040, it is crucial to begin development as soon as possible, focusing on promising technologies and executing precursor missions that serve as technological demonstrators.

The first precursor mission should aim to demonstrate and validate technologies such as solar sailing and spacecraft operations around the L_1^* point. Paramount it will be to gather data on the orbital environment at L_1^* and study long-term effects on the spacecraft, such as membrane degradation in solar sails. The details of a planetary sunshade precursor

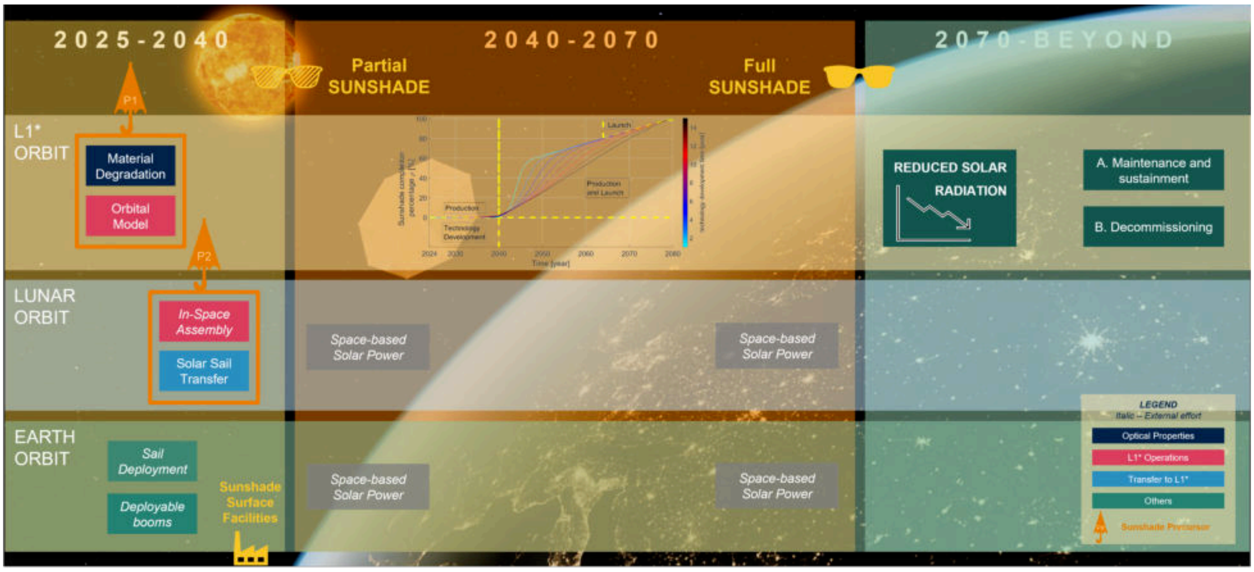

Figure 3: *A preliminary technology roadmap for the planetary sunshade programme.*

mission concept are presented in [51]. With an estimated budget needed for the precursor mission of the order of tens of US millions, this mission represents a tangible step forward.

Then, series of progressively more complex precursor missions should be planned, each of which introduces more advanced technologies and operational challenges. Some of these missions can be conducted within the Earth-Moon system, such as in-space automatic assembly and the operation of smaller swarms flying in formation.

5.2 Key Technologies and Materials

One of the central technologies required for the Planetary Sunshade is the development of the membrane that will form the sunshade itself. While existing solar sail membranes are relatively easy to produce and could serve as initial sunshades, they are not optimized for minimizing the overall mass of the structure. Ideally, these membranes should utilize diffraction or interference to redirect sunlight away from Earth, significantly reducing the total mass required [19, 21, 52]. The roadmap should include a focused effort on developing and mass-producing such membranes cost-effectively. Until these advanced membranes are available, conventional solar sail membranes will be used.

As humanity will likely establish lunar bases in the 2030s and begin to harness lunar resources in the 2040s, manufacturing sunshade components and rocket propellant on the Moon might become feasible and economically advantageous. The roadmap should anticipate a transition from Earth-based to Moon-based manufacturing during the decades-long process of constructing the Planetary Sunshade. Continuous improvements and efficiency gains are expected throughout this period.

5.3 Launch and Deployment Strategies

SpaceX´ Starship is expected to lower launch costs by a factor of 50-100. However, there is no reason to think of Starship as the ultimate exclusive launcher. It is certainly a trailblazer that will show what is possible, but even that can be improved and versions optimal for various purposes will be designed. With millions of tons foreseen to be launched for the whole Planetary Sunshade, there should be an optimal launcher designed specifically for this, most likely building upon Starship heritage. The Roadmap must take this into account.

5.4 Environmental and Safety Considerations

Despite being one of the less risky geoengineering methods, the potential negative effects of a Planetary Sunshade must be thoroughly investigated.

This includes analysing the environmental impact of rocket exhausts, the carbon footprint of manufacturing processes, and the potential creation of NOx in the stratosphere due to reentry of launch vehicles. Additionally, the roadmap should address how best to implement latitude variations in the sunshade [23].

5.5 Roadmap Infographic

A preliminary technology roadmap is produced in the infographic in Figure 3. The goal is to provide to the reader a potential roadmap structure, with no claim to provide a roadmap completed with all the necessary development steps for the sunshade programme.

As for the considerations of the previous sections, the roadmap timeline is divided into three sections (vertical): before 2040, until 2070, and beyond. A further categorisation is performed with three rows per orbit characterisation: earth, lunar, and L_1^* orbit.

Many of the technological developments needed by the planetary sunshade are of interest for a number of other missions and applications. For this reason, the roadmap includes development efforts not uniquely driven by the sunshade programme. Some examples of these developments are reported in the infographic in *italic*, e.g. the development of deployable booms or in-space assembly. Such specification is important considering the possible reduction for the economical effort required by the whole planetary sunshade programme. Moreover, precursor missions can be defined with the goal to develop one or more technologies within the same mission. In the infographic, a grouping example is depicted with orange frames.

During the planetary sunshade operations it will be necessary to define specific milestones for the programme and direct or indirect development of technologies that can be transferred also for other missions, applications, or orbit environment, e.g. space-based solar power missions can benefit from the sail technology developed by the sunshade programme.

Similarly, in the *beyond* part of the timeline, it is possible to define the technology transfer generated by the programme and the possible envisioned scenario for the programme itself, i.e. to maintain and sustain the system or to decommission it.

6. Risks and Costs

The development of the PSS entails significant risks and costs, which necessitate careful consideration and planning to ensure the project's success. The primary risks associated with the project include the probability and severity of damages to individual units of the sunshade, as well as the challenges of mitigating these risks without compromising the overall system.

6.1 Damage to Sunshade Units

The Planetary Sunshade System, being composed of potentially thousands or millions of individual solar-sail satellites, is susceptible to damages from micrometeoroid impacts, radiation, and mechanical failures during deployment. Each unit's damage could potentially impair the system's effectiveness, but the design must ensure that such damages do not lead to catastrophic failure of the entire system. This requires the implementation of a robust fault-tolerant system and redundancy in satellite deployment and operation.

6.2 Logistical Risks

The complex logistics involved in manufacturing, launching, and assembling the sunshade units present significant risks. These include potential delays in production, unexpected failures during launch, and challenges in assembling and coordinating the sunshade in space. The project must account for these risks by developing contingency plans, ensuring flexibility in the project timeline, and securing reliable international partnerships for various stages of the project.

6.3 Technological Risks

The technology required for the PSS, such as the solar sails, launch vehicles, and assembly mechanisms, involves cutting-edge developments that may face unforeseen challenges. The low TRLs of some of these technologies add to the risk profile, emphasizing the need for ongoing research, development, and testing to mitigate technological risks.

6.4 Manufacturing Costs

The production of millions of solar-sail satellites represents a significant cost driver. This includes not only the material costs but also the costs associated with developing new manufacturing facilities, workforce training, and quality assurance processes. The choice of materials, such as lightweight reflective coatings and durable membranes, will heavily influence the overall costs.

6.5 Launch Costs

Launching the sunshade units into space is another major cost factor, in terms of units production, propellant and launch and production sites. With advancements in space launch technology, such as the development of SpaceX's Starship-Superheavy, the cost per kilogram to space is expected to decrease. However, the sheer volume of material to be launched means that total launch costs will still be substantial. The need for multiple launch sites and the coordination of frequent launches add to these expenses.

6.6 Operational Costs

Once deployed, the sunshade system will require ongoing operations and maintenance, including station-keeping, monitoring, and potential repairs or replacements of damaged units. The costs associated with these operations must be included in the overall budget, along with provisions for unforeseen operational challenges.

6.7 International Collaboration and Coordination

The scale of the Planetary Sunshade project necessitates international collaboration, which introduces additional costs related to coordination, regulatory compliance, and the establishment of international agreements. These costs, while not directly linked to the physical construction or deployment of the sunshade, are crucial for the project's success and sustainability.

7. The Policy Context

European Union (EU) has taken a leadership role in climate change mitigation, encapsulated in the European Green Deal. This ambitious initiative aims for the EU to become climate neutral by 2050, with a significant milestone of a 55 reduction in greenhouse gas emissions by 2030, relative to 1990 levels [53]. The European Climate Law enshrines these targets, demonstrating the EU's commitment to sustainable development and the deployment of green technologies. To achieve these goals, the EU has implemented policies promoting renewable energy, enhancing energy efficiency, and fostering green job creation. The European Environment Agency (EEA) provides detailed monitoring and reporting on the progress of these initiatives, maintaining a comprehensive database of national policies and measures adopted by member states.

On a global scale, effective climate change mitigation necessitates coordinated international efforts. The International Monetary Fund (IMF) emphasizes the critical role of international cooperation in climate policy, facilitating frameworks that allow for the comparison and alignment of climate mitigation strategies across different nations [54]. Global agreements such as the United Nations Framework Convention on Climate Change (UNFCCC),the Intergovernmental Panel on Climate Change (IPCC) and the Paris Agreement underscore the importance of collaborative efforts to reduce greenhouse gas emissions. These international frameworks support innovative solutions like PSS, which proposes the deployment of a solar light umbrella in space to regulate the solar radiation reaching Earth and mitigate global warming.

Integrating space-based climate mitigation strategies into existing policy frameworks poses significant technological, logistical, and cooperative challenges. The development of a PSS necessitates advancements in space engineering, robust international collaboration, and thorough environmental assessments. The supportive context provided by European and global policies facilitates the exploration and potential implementation of such advanced technologies [55, 54].

8. Conclusions

This paper presents a roadmap for a space-based solar geoengineering programme, aimed at reversible solar radiation modification to mitigate global warming though a Planetary Sunshade System.

This roadmap includes the main aspects to address the full development of a Planetary Sunshade System, considering the involved technologies for the solar sail materials, deployable structure and mechanisms, launchers, and AOCS & swarm logistics at the photo-gravitational L_1 point. Then, the phases are outlined in chronological order highlighting the critical and operative factors during the deployment of the Planetary Sunshade Programme. Finally, political challenges are discussed, in terms of international context and risks and cost associated.

The proposed roadmap serves as both an initial framework for designing and developing the Planetary Sunshade System, and as a key analytical tool to assess the viability of implementing direct climate intervention from space.

Acknowledgements

For the author Marina Coco this publication is part of the project PNRR-NGEU which has received funding from the MUR – DM 118/2023.

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