Enhancing Terrestrial Solar Power Using Orbiting Solar Reflectors†

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Abstract

The delivery of global clean energy services represents a key challenge for the 21st century. In order to deliver such services, it is clear that large-scale solar power farms will continue to grow both in number and size. In principle, ultralight membrane orbiting solar reflectors can illuminate large-scale solar power farms during the critical dawn/dusk hours of the day, enhancing the utility of terrestrial solar power. The key advantage is that only a relatively modest mass needs to be delivered to Earth orbit. This paper discusses the technical challenges associated with the development, deployment and operation of such a space-based energy service. Business development models are discussed along with regulatory issues and finally an integrated technology demonstration roadmap is presented.

Keywords: space-based solar power, orbiting solar reflectors, solar energy

1. Introduction

The concept of orbiting solar reflectors has a long history, pre-dating the modern space era. Early visionary work by Oberth in the 1920s proposed large reflectors deployed in polar orbit to be utilised for a range of applications including illumination, navigation, cloud dispersal and enhancing agricultural output amongst others [1]. Oberth's detailed analysis covered the impact of solar radiation pressure on the reflector orbits, gyroscopic attitude control and in-orbit assembly strategies. Indeed, he noted that solar radiation pressure would displace a reflector on a polar orbit in the anti-Sun direction, understood now as one of a family of non-Keplerian orbits [2].

These early visions were developed further during the 1960s, with studies to investigate applications of orbiting solar reflectors for localised terrestrial illumination. Buckingham and Watson considered night-time illumination levels which may be possible for a given reflector size, along with design concepts for large, lightweight reflectors utilising radial spokes and a central guy mast for tensioning a reflective membrane [3].

Later in the 1970s Billman et al. proposed constellations of large numbers of solar reflectors specifically for terrestrial power generation, as an alternative to both conventional power plants and the power beaming strategies of solar power satellites [4]. Power conversion using ground-based collectors with solar cells or solar thermal power were considered. As a novel addition, relay mirrors were also investigated to distribute collected solar energy around the constellation to specific ground locations [4]. Rush also considered the concept of orbiting solar reflectors for night-time illumination of urban areas [5].

A detailed and systematic investigation of orbiting solar reflectors was provided by Ehricke, who envisaged a range of reflector concepts optimised for different applications. These included so-called *Lunetta* reflectors for low-level local illumination of urban and rural areas and *Powersoletta* reflectors to enhance solar energy generation during the day or to deliver solar energy at night [6]. Using very large numbers of reflectors Ehricke's concept would help remove the diurnal, latitudinal and seasonal variations in solar power plant output.

Following Ehricke [6], NASA studies in the 1980s investigated the use of 1 km diameter reflectors with a launch mass of the order of 11 tonnes using control moment gyros for attitude control [7]. Interestingly, the reflector mass per unit area of 14 gm^{-2} is not dissimilar to that envisaged by Oberth (10 gm^{-2}) decades earlier [1]. The reflectors would be deployed from the Space Shuttle and then delivered to their operational orbit using solar radiation pressure. Applications included the illumination of large urban areas and on-demand illumination to support disaster relief [7]. Approximately the same time as this NASA study, the so-called the 'Moon-Day Project' was studied by Salmon, in which reflectors were proposed to be installed on the Moon to provide additional illumination for a variety of applications, similar to NASA studies [8]. Salmon discussed a number of parameters for the reflectors,

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including their location on the Moon and illumination levels on the Earth, and argued for their utilisation for India, central Africa and northern America [8].

More recently, Potter and Davis considered the use of orbiting solar reflectors as a stepping stone to large-scale space solar power systems [9]. They note that by illuminating terrestrial solar power plants, the mass required in orbit is significantly less than that for conventional space solar power. However, they also note that low orbits are required to ensure that the projected image of the solar disk is small, which leads to short duration passes [9]. A further useful review of the development of orbiting solar reflectors and their applications is provided by Lior [10].

Other recent studies of orbiting solar reflectors by Fraas et al. have also focused on applications for terrestrial solar power [11, 12, 13]. They envisage a constellation of 18 reflectors (each comprising a 10 km diameter array of individual 1 km reflectors) in a 1000 km polar orbit servicing some 40 solar power plants. The reflector concept is based on extrapolations of current technology; inflatable booms to deploy and rigidize the membrane reflector and control moment gyros to generate sufficient slew rates for attitude control. Fraas et al. also proposed the International Space Station as a location to demonstrate additional illumination at full-moon intensity using a 12 m^2 reflector as a step towards space-based solar power systems [14]. Fraas then extended their proposed concept to evening street lighting using a four-reflector satellite constellation on 6504 km altitude polar Sun-synchronous orbits [15]. Most recently, Fraas and O'Neill proposed Fresnel lenses for a Solar Power Satellite demonstration [16], which is a concept that may also be considered for orbiting solar reflectors.

Further recent studies include Bonetti and McInnes who considered the use of so-called heliotropic orbits. These are elliptical equatorial orbits whose apse line is artificially precessed using solar radiation pressure to ensure that the orbit perigee is always directed to towards the Sun [17]. This enables a long dwell time for the reflectors over the night-side of the Earth at the orbit apogee.

Amongst the studies focusing on more specific aspects of orbiting solar reflectors include Ashurly, who used a ray-tracing approach to compute the solar energy that can be delivered from a 36000 km altitude orbit (i.e., approximately geostationary Earth orbit (GEO)) by single and compound reflector systems [18]. Ashurly studied the effect of orbital position and attitude angle on the quantity of energy delivered to ground [18].

Practical experience with orbiting solar reflectors has included the 20 m diameter Znamya reflector deployed from a Progress T-15 cargo vehicle after undocking from the Mir space station in 1993. The spin-stabilised reflector deployed successfully and a bright spot, an image of the solar disk, was seen to be projected on cloud tops by observers on the Mir space station. The sunlight from the reflector was also apparently observed from the ground as the reflector orbit passed over central Europe. A larger experiment using a 25 m diameter reflector was attempted in 1999 but was unsuccessful after the reflective membrane snagged on an antenna during deployment.

Other in-orbit demonstrations have included the NASA Inflatable Antenna Experiment, a 14 m diameter reflector deployed from the Space Shuttle in 1996 [19], whose image can be seen in Fig. 1. Moreover, there is now experience of ground testing and in-orbit deployment of solar sails which provides a pathway to the much larger reflectors required for solar power applications [18].

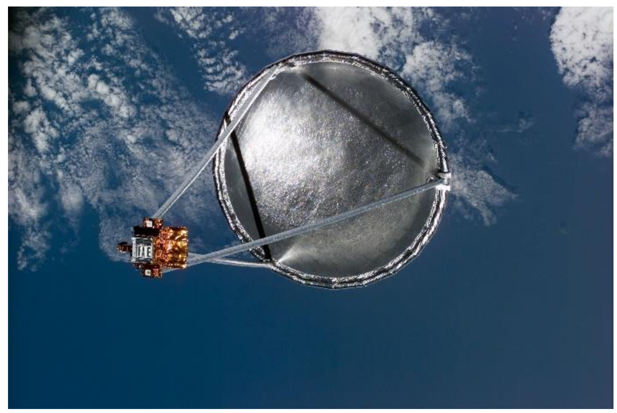

Fig. 1. 14 m diameter Inflatable antenna experiment STS-77 1996 (NASA)

A general overview on controlling illumination on the surface of the Earth by space-based systems is discussed by Starovoytov, in which the author discussed the practical aspects of reflectors, including structures, deployment and control, as well as operational aspects, including end-of-life disposal of the reflectors and ecological impacts of additional illumination [21].

Other applications of solar reflectors can be envisaged including lunar night illumination [22], asteroid resource processing [23], long-term applications for climate engineering [24] and speculative applications for terraforming [25] which are not considered here.

In this paper, the technical challenges of the employment of orbiting solar reflectors will be discussed for terrestrial solar energy applications. This will include the development, deployment and operation of such a space-based energy service. Business development models will also be discussed along with regulatory issues and finally an integrated technology demonstration roadmap will be presented.

The paper is structured as follows. In the next section, an overview of the concept of orbiting solar reflectors will be presented in detail alongside a comparison with solar power satellites. In Sec 3, orbit selection will be discussed, which will be followed by reflector attitude control in Sec. 4 and reflector configurations in Sec. 5. Economics and business models will be presented in Sec. 6. Regulatory issues related to the operation of reflectors will be discussed in Sec. 7 and an integrated technology roadmap will be presented in Sec. 8. Finally, conclusions are presented in Sec. 9.

2. The Concept of Orbiting Solar Reflectors

In order to deliver clean energy services for the 21st century it is clear that a range of new technologies will need to be deployed at a sufficient scale to have impact on the global energy economy. For example, as the cost of terrestrial solar energy falls, economies of scale may drive utility-scale solar power plants to ever-larger sizes [26]. Large desert or floating solar power plants can be envisaged with multi-kilometre length-scales [27]. Concepts also exist for 'solar breeder' architectures which utilise in-situ silica in desert locations to fabricate ultra-large solar power plants [28]. However, even for largely cloud-free locations, the diurnal day-night cycle (and seasonal cycles, depending on latitude) may severely limit the utility of such installations. Moreover, while solar power plant output peaks close to local noon, peak demand and energy spot prices are typically in the evening when output is low or indeed vanishes due to low elevation of the Sun [29].

Bridging the mismatch between power plant output, whether diurnal or seasonal, and energy demand, is a key constraint on the future expansion of solar power on a truly global scale. At present solar energy only has a small market share of global primary energy, but has the capability to grow to multi-terawatt scales [30]. If this market share is to grow sufficiently to impact on decarbonisation, then bold thinking is required. While a range of energy storage technologies are available, which can store and shunt solar power plant output, the requirement for diurnal and seasonal energy storage capacity at a global scale is potentially vast [31]. However, orbiting solar reflectors can in principle help ensure that the market share of solar energy can grow to a scale where it will impact on decarbonisation [32].

Orbiting solar reflectors offer an exciting strategy using ultra-lightweight membrane structures to enhance the delivery of clean energy from terrestrial solar power plants. The key advantage of the orbiting solar reflector concept is that the mass required in Earth orbit is small, particularly relative to conventional space solar power architectures using wireless power transmission. However, Potter and Davis also note that orbiting solar reflectors can also provide a stepping stone towards large-scale space solar power [9].

The strategy itself would utilise a constellation of orbiting solar reflectors (Fig. 2, 3) to illuminate ultra-large terrestrial solar power plants, particularly at dawn and dusk, when their output is low but energy demand and spot prices are high. Importantly, by using this strategy there are no direct interfaces with or impacts on terrestrial solar power plants. Indeed, it is clear that large-scale terrestrial solar power plants will be constructed in the coming decades, independent of the space sector, and so much of the development required for the utilisation of orbiting solar reflectors is decoupled both technologically and economically from the space sector itself. Simply illuminating solar power plants at times of high demand, but low output (dawn, dusk or night), will allow utilities to continue to sell energy to the grid when spot prices are high.

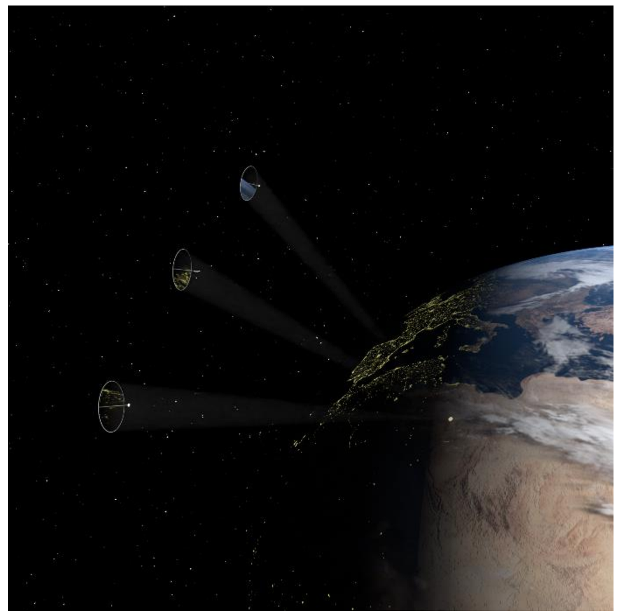

Fig. 2. In-orbit representation of a train of reflectors (reflector size not to scale) reflecting sunlight to a terrestrial solar power plant (Earth texture map, NASA)

Such a scheme can underpin the delivery of an entirely new service for the space sector, the delivery of energy, rather than the delivery of data services. Such an energy service is both global and scalable and can be expanded incrementally; from low cost, small-scale in-orbit demonstrations towards the delivery of large-scale services to global energy utilities.

To illustrate the potential of orbiting solar reflectors, consider now the scaling-laws which underpin their use. An orbiting solar reflector of areal density σ and orbit speed v has a kinetic energy per unit reflector area that scales as $\sigma v^2/2$. Moreover, for solar flux F acting over time τ, the energy intercepted per unit area scales as $F\tau$. Then, for a reflector with an areal density of 10 gm^{-2} the time τ required for the reflector to intercept a quantity of solar energy equivalent to its kinetic energy is only of the order of a few minutes. As will be seen later however, there are significant geometric and atmospheric losses which need to be accounted for in terms of the final energy delivered to the grid.

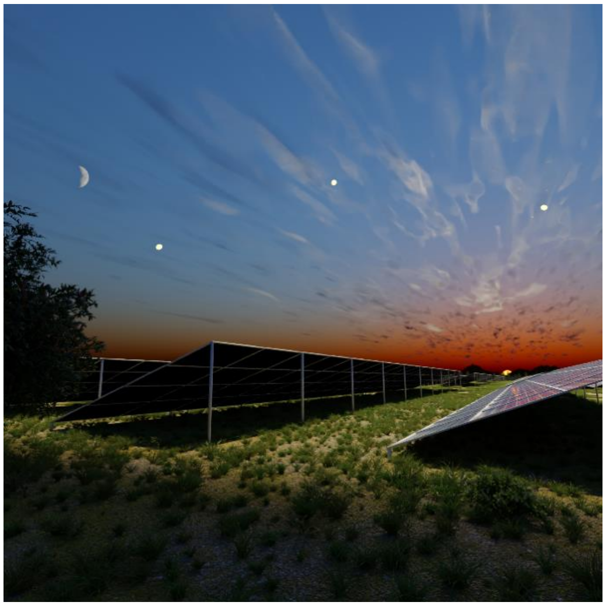

Fig. 3. Representation of the solar power plant and reflectors during sunset as seen from ground.

Moreover, the power-to-mass ratio of the reflector scales as F/σ, which for a reflector with the same areal density is of order 140 $kWkg^{-1}$. If such a reflector were configured as a disk with a diameter of one kilometer, it would intercept of order 1 GW of power, but would have a mass of only 8 tonnes. With the advent of reusable, heavy lift launch vehicles delivering over 100 tones to Earth orbit, a constellation of such reflectors could be quickly deployed. Such reflectors could be conventional deployable structures [7, 11, 12], or could be fabricated in orbit to enable ultra-lightweight gossamer reflectors, thus overcoming the limits imposed by launch loads and the launch vehicle payload faring volume [33].

It can be seen that there is now a timely superposition of a strongly growing demand for clean energy services in the coming decades, falling launch costs (and growing launch mass) and the advent of in-orbit fabrication technologies which makes orbiting solar reflectors an attractive and scalable proposition for the 21st century.

Before discussing the technical details of the reflectors however, it is useful to present a comparison with solar power satellite using wireless power transmission. This will illustrate how those two concepts differ and how they can complement each other towards the same goal of delivering clean energy.

2.1. Trade-off with Solar Power Satellites

Another broadly studied concept for harnessing power from space is Solar Power Satellites (SPS). A good summary of the development of SPS and some of its challenges is discussed in [34]. SPS differs from the orbiting solar reflectors discussed in this paper. Several differences exist between both technologies in terms of operations and use. Some of these differences are outlined below:

i. *Space Structure and Mass*:

With orbiting solar reflectors, sunlight is reflected to illuminate large solar farms on the Earth for energy production. The reflecting surface and supporting structure for control and associated subsystems make up the entire space segment. Orbiting solar reflectors are therefore relatively light weight compared to SPS as the energy conversion system is entirely ground based.

In contrast, for SPS, in addition to the collecting surface, the conversion system which converts light to microwave energy and the transmission system which delivers the microwave energy to an Earth ground station are required. In that regard, the SPS system can be considered as a standalone solar power plant in space, and therefore a significantly heavier space system. The development, assembly and transportation of a SPS system in principle takes longer and the process is more complex than that for orbiting solar reflectors.

ii. *Ground Station Facilities:*

The illumination from orbiting solar reflectors is used directly by solar farms to produce energy. No extra adaptation is required by the solar farms. Furthermore, as highlighted in [6, 7], this illumination can be used for other activities such as agricultural production, night-time illumination and other applications.

For SPS, dedicated facilities need to be built including a rectenna to receive the microwave energy and a converter which converts the microwave energy transmitted from space into electrical energy for use on the Earth.

iii. *Environmental Effects:*

Stray light pollution and additional heat released into the atmosphere are the two most likely effects of orbiting solar reflectors. However, reflectors can also be controlled to reflect light away from the Earth when not in use thereby reducing stray light issues. If the energy delivered is used to displace fossil fuel use (and the subsequent time integrated impact of atmospheric CO_2) the net impact on the climate will be beneficial.

The possible impact of microwave energy is the main environmental effect of SPS. The potential for microwave energy to heat the ionosphere and consequently interfere with communication systems [34] is an issue. Similarly, due to the numerous launches required to transport heavy SPS systems into orbit, there may be greater emissions delivered.

iv. *Operational Orbit*:

Orbiting reflectors are usually considered for low Earth orbit (LEO). A reflector therefore has a limited visibility period to pass over any location on the Earth, so multiple reflectors will likely be required to provide extended illumination to a given location and so extended energy delivery. However, orbiting solar reflectors can in principle visit multiple solar power farms in a day, provided that those are on the ground track of the reflector, hence the limited time spent over solar farm can be compensated.

Furthermore, the area illuminated by a reflector is large, i.e., solar image size is dependent on orbit altitude, which will be discussed in more detail in the next section. This means that, for example, if placed in GEO, the size of the illuminated spot will be extremely wide, covering a diameter of approximately 336 km, hence only LEO is considered here.

On the other hand, SPS is considered to be placed in GEO and can be used for constant energy delivery (baseload energy provision) on Earth. An SPS in GEO means continuous access to the ground site, and virtually eclipse-free solar power collection, but also means long path losses in delivery. Nevertheless, SPS systems are not usually considered for LEO.

v. *International Dimension:*

Orbit allocation for smooth operation of satellite systems in space is managed in conformity with international regulations and the United Nations Outer Space Treaty.

Orbiting solar reflectors can be placed in several orbits at different orbit altitudes and inclinations. With options for a range of orbital altitudes possible, securing an orbit for the reflectors is potentially less challenging than limited slots in GEO.

For the SPS system, which is usually placed in GEO, securing a GEO orbit is more competitive and challenging than other orbit altitudes. GEO is a prime orbit which hosts numerous critically important satellites such for telecommunications and Earth observation amongst others. Furthermore, allocation of frequency bands for microwave power beaming presents a challenge. Desired frequency bands are limited, and it is important to prevent interference with other communication systems. Moreover, given that microwave energy does not respect national borders, internationally agreed standards for microwave power levels are required.

After presenting this comparison, the remainder of the paper will focus only on orbiting solar reflectors and address the opportunities and challenges, in terms of technologies, business models and regulations.

3. Reflector Orbit Selection

Reflector orbit selection is driven by several competing parameters. In order to understand these parameters, it is necessary to understand the relationship between the size of solar image reflected on a ground target and the orbit altitude. During an overhead orbital pass, the image of the solar disk reflected on a ground target (e.g., a solar power farm) first takes the shape of a stretched ellipse, then gradually becomes circle at the zenith point, before stretching again as the reflector recedes in horizon. While the exact shape and size of the ellipse is a function of elevation, hence time, its dependence on orbit altitude can be understood when the reflector is at the zenith above the ground target, i.e., the image of solar disk is circular, as shown in Fig. 4.

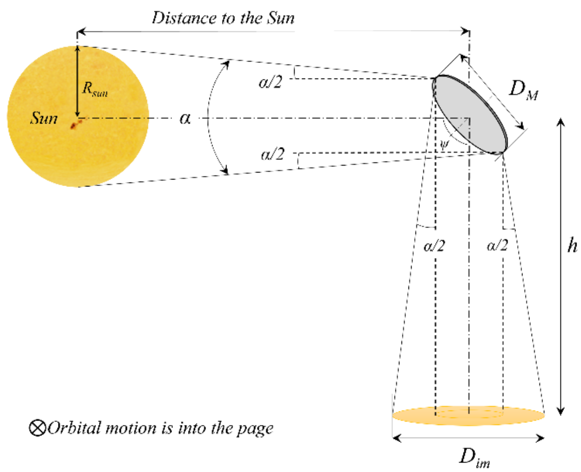

Fig. 4. Geometry of the solar image at zenith point of an overhead orbital pass. Image is not to scale (adapted from Ref. [7]).

It can be seen from Fig. 4 that the diameter of the solar image at zenith point, D_{im} is a function of the reflector diameter D_M, the orbit altitude h and the angle (α) subtended by the Sun due to its finite size at 1 Astronomical Unit (AU), (defined as the mean distance of the Earth from the Sun, i.e.,1.5 x 10^8 km). It will be assumed that the finite size of the reflector D_M can be ignored as it is small enough in comparison to the orbit altitude and the size of the solar image. The α angle is calculated as approximately 0.01 radians using the radius of the Sun, R_{sun} and the distance of the Earth from the Sun. D_{im} can then be expressed as $D_{im} = h\tan(\alpha)$ and can be approximated as $D_{im} \approx h\alpha$. Then, for example, the diameter of the solar image would be equal to approximately 10 km at a 1000 km altitude orbit at the zenith point of the orbital pass. The solar power collected is constant for a given reflector size and orientation; therefore, the size of solar image and orbit altitude determines the solar power density on the ground. However, in order to maximise the duration for which solar energy is delivered to a solar farm, it is desirable that the orbital pass over a given solar farm is long. This implies higher orbit altitudes from a simple geometric analysis of Keplerian orbits. The trade-off between short pass duration and high solar power density, and long pass duration and low power density stands as the first challenge for reflector orbit selection. The high solar power density achieved at lower altitudes comes at a cost of stronger perturbations experienced by the reflector, among which are Earth's oblateness and atmospheric drag. High altitude orbits in principle experience lower levels of perturbations such as atmospheric drag, but in this case the solar power is delivered at much longer slant ranges, decreasing the effectiveness of the reflectors. Orbit altitude selection is also driven by the finite size of a solar farm. The shape of the illuminated region changes during an orbital pass, ranging from an infinitely stretched ellipse to a circle at the zenith point, whose approximate dimensions are presented above, before stretching back as the reflector wanes in the local horizon. Optimising the reflector orbit altitude to deliver the maximum quantity of solar energy to a solar farm is another aspect of the trade-off, which will be discussed in more detail, together with potential candidate orbits.

To offset the shortage in solar power in critical dawn/dusk hours, Sun-synchronous orbits (SSOs) appear as the prime family of candidate orbits. SSOs are a special class of near-polar orbits, whose orbital plane precesses due to the oblateness of the Earth at an angular rate matching the orbital motion of the Earth around the Sun. As a result, a SSO would visit a given location always at the same local time of day. In principle, dawn-dusk SSOs do not experience eclipses, allowing for a continuous capability to deliver solar energy. Therefore, appropriately selected orbital elements would allow the SSO to visit selected solar farms at specific dawn/dusk hours. The SSO condition dictates a coupling between semi-major axis (a), eccentricity (e) and inclination (i) of an orbit from the perturbed orbital motion [35]. Figure 5 below shows the relationship between orbit semi-major axis, eccentricity, and the corresponding inclination for the SSO condition to be realised, for the case of the second zonal harmonics (i.e., J_2) considered for the perturbation of Earth's oblateness.

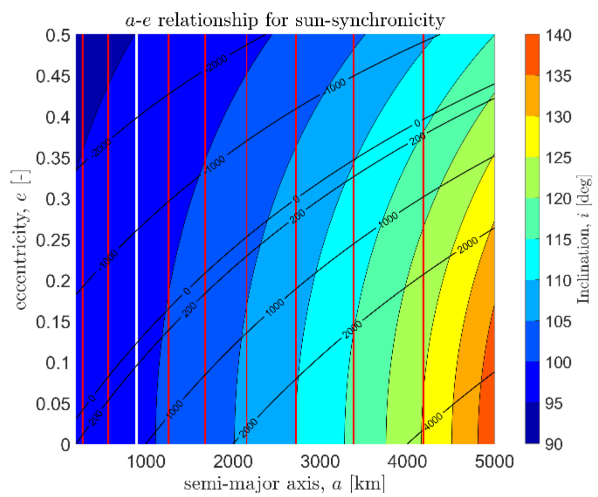

Fig. 5. Semi-major axis – eccentricity space of SSOs. Colour bar denotes inclination of SSOs at a given semi-major axis and eccentricity. Black numbered contours denote periapsis distance, vertical lines denote the semi-major axis of orbits that repeat their ground track every 24 h. White line denotes 894 km altitude discussed in the paper.

The SSOs have typically been considered as circular orbits for solar reflector applications in the literature [12]. However, elliptical SSOs expand the catalogue of possible SSO-type reflector orbits significantly, as shown in Fig. 5. For example, eccentricity and other orbital elements may be selected such that the reflector's pass over a given solar farm optimises the solar image size, and hence the delivered solar energy. Furthermore, elliptical SSOs with potentially very low-altitude perigees may be exploited in which the perturbations experienced at low altitudes may be compensated at the apogee phase by using solar radiation pressure. These opportunities will be explored in the future.

Moreover, due to the orbital dynamics associated with the oblate Earth, higher altitude SSOs are inclined such they can be over mid-latitudes in the northern hemisphere during night-time. This feature of SSOs, combined with longer pass durations due to high altitude and the absence of eclipses, may also allow solar power delivery at night-time to solar power farms in mid-latitude regions, further enhancing the capabilities of the concept of orbiting solar reflectors. It is worth noting, however, that a range of SSO altitudes experience temporary eclipse periods each year due to the tilt of the Earth's polar axis [9]. Orbit altitudes must then be selected from those that do not experience eclipses or the impact of eclipse periods in the overall economic and business case must be analysed in more detail.

In order to ensure daily solar energy delivery to solar farms, repeating ground track (RGT) orbits can be selected. RGT orbits complete an integer number of orbits in a given period of time (e.g., 1 day) such that due to the Earth's rotation, the ground track periodically returns to same point [35]. An orbit can be both SSO and RGT. Because RGT is a property of the orbit period, it can be considered for elliptical orbits, particularly for elliptical SSOs. The RGT property can then be used to select the reflector orbit together with the other design parameters. For example, one example could be a circular SSO at ~894 km altitude (denoted by a white vertical line in Fig. 5). At this altitude, the orbit period is equal to ~1.7 h, and each visit would allow approximately ~16.5 minutes of solar energy delivery. The orbit would also complete 14 orbits in a day, which means that the 15th orbit would revisit the selected solar farm, exactly 24 hours after.

Finally, multiple trade-off parameters can be used to design a constellation of reflectors to deliver the desired level of solar energy. The simplest type of constellation may be a number of reflectors at the same SSO orbit altitude, with the orbit planes closely spaced and the reflectors phased such that quasi-continuous solar energy delivery is achieved for a duration that is determined by the number of reflectors and their phasing. It should be noted that there are also limits on how far into the night-time a reflector orbit can be placed before experiencing eclipse.

It is likely that a simple constellation will be too restrictive for a range of solar farm locations, size and desired revisit times. Then, a more complex constellation, which would comprise a mix of circular and elliptical orbits at different altitudes and spaced such that the energy delivered is maximised through both optimising the solar image size and the number of passes over the solar farms. Moreover, more agile, and flexible constellations are likely to be required to reconfigure the orbit geometry to address business demands and latitude dependent seasonal variations.

In order to successfully employ those constellations in the orbits discussed, attitude control must also be provided, such that the reflector can point and reflect the incoming sunlight towards a target solar power farm. The attitude control aspects of orbiting solar reflectors will therefore be discussed next.

4. Reflector Attitude Control

The attitude control system must provide the necessary torques during tracking and reorientation manoeuvres, such that sunlight is continuously reflected to a solar power farm during the tracking phase, while rejecting external disturbances, such as torques due to solar radiation pressure (SRP), gravity gradient or atmospheric drag. Depending on the orbit altitude, the equivalent angular accelerations associated with each of these effects (and hence the required control torque) will vary, potentially leading to different attitude actuator choices. Furthermore, the control torque is proportional to the reflector inertia, i.e., to the product between the reflector areal density and the fourth power of the reflector size. For a fixed areal density, it is immediately clear this scaling law penalizes larger structures.

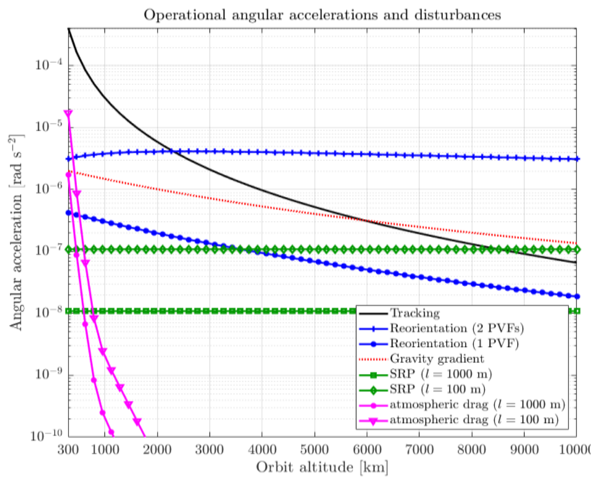

Fig. 6. Angular acceleration due to operational manoeuvres and disturbances. A 0.25% offset between the centre-of-pressure and centre-of-mass was assumed for the calculation of the SRP disturbance.

If the reflector is on a circular dawn-dusk quasi-polar SSO, the main tracking control mode comes from north-south steering, necessary to change the latitude of reflected spot, based on the solar power farm location. The east-west control mode can be reasonably neglected for orbits with altitudes below 5000 km, as the orbital period is much smaller than the Earth rotation period: thus, the reflector must be tilted at a constant 45 deg angle with respect to the orbital plane. Tracking of the solar farm is then guaranteed if the reflector is above the local horizon of the solar power farm. Ideally, in the absence of obstacles or physical obstructions (e.g., mountains), the reflector could span a 180 deg elevation angle during the tracking manoeuvre. The reflector must then be reoriented to ensure sunlight is reflected to the next solar power farm to be tracked along the orbit. Figure 6 illustrates the peak angular acceleration required during the tracking (black line) and reorientation (blue line) phases as a function of the orbit altitude (see Ref. [36] for additional details). Also shown are the equivalent gravity gradient and solar radiation pressure peak angular accelerations. The reorientation angular acceleration is calculated assuming tracking of two solar farms located at the equator 180 deg apart in longitude. Aerodynamic drag rapidly decreases and is negligible for orbit altitudes greater than 1000 km. The north-south tracking effort dominates at lower altitudes, up to approximately 2000 km, where the reorientation acceleration dominates over other perturbations. For example, on a 1000 km orbit, the peak angular acceleration is on the order of 3 x 10^{-5} rad s^{-2}. It can be shown that the effort required during the reorientation manoeuvre can be reduced if both sides of the reflector are reflective, however such a reduction is smaller than one order of magnitude and the reorientation effort would still dominate over the other perturbation at higher orbits.

A reasonable estimate of the required control torque is then given by the product between the peak angular acceleration and the reflector inertia about the rotation axis. A larger control effort will be therefore required at lower altitudes. Assuming a square reflector with inertia 1/6 σl^4, where l is the reflector side length and σ is the areal density, by fixing the reflector areal density to 10 gm^{-2} the control torque scales as $5 \times 10^{-8}\, l^4$. For example, a 100 m structure requires control torques of order 10 Nm, which increases by a factor 10^4 for a 1 km structure, which is the reflector size proposed in previous studies [7]. Furthermore, if momentum exchange devices are used, their stored angular momentum must be at least equal to the peak angular momentum during the manoeuvre. This can be estimated as the product between the reflector inertia and the peak angular velocity during the manoeuvre. For example, at a 1000 km altitude circular polar orbit, orbital dynamics implies a peak angular velocity of approximately 0.4 deg/s, resulting in an angular momentum capacity of $7 \times 10^{-5}\, l^4$ Nms.

Typically, control moment gyros (CMG) represent the primary actuator choice when dealing with large space structures with large control torques requirements. For reference, a single CMG on the International Space Station has a nominal angular momentum capacity of 4760 Nms and can provide a torque of 258 Nm. Using the scaling laws discussed above, the maximum reflector size that could be controlled in such conditions is approximately 180 m. To meet the torque and angular momentum requirement for larger structures, thus enabling higher energy transfer to the solar farm, the use of large-diameter momentum wheels have been speculated in previous space reflector designs. For example, in Ref. [7] it is proposed to use a pair of two large deployable 'isotensoid' wheels, with a 20-metre diameter after deployment. Another solution would be to install an annular ring rotating at the edge of the reflector (which must be circular in this case) or using a spinning fluid at the edge of the reflector. The latter solution would avoid issues related to moving mechanical parts. Alternatively, as proposed in Ref. [36], a pair of CMGs could be appended at the top of two booms normal to the reflector, as shown in Fig. 7. It can be shown that if the wheel mass is 1/24 of the reflector mass (neglecting the boom mass), the inertia of the reflector about the three principal axes is equal. Thus, not only is the gravity gradient torque cancelled but also any precession torque resulting from a rotation about a non-principal axis is removed, therefore enhancing manoeuvrability. In any case, all such solutions come with additional related issues, for example related to the gimballing of such large momentum exchange devices or to structural vibrations.

Reaction wheels are not suitable for large control torques, due to their large power requirements. It can also be shown that the required reaction wheel mass is one order of magnitude larger than a control moment gyro mass, for a given output torque requirement.

Due to the large reflector area, a further possibility is to exploit solar radiation pressure to produce control torques. This can be achieved, for example, using sliding masses moving on rails attached to the reflector structure. By displacing the masses, the centre of mass of the reflector can be changed, thus producing a torque. However, it can be shown (see Ref. [36]) that due to the fourth-power inertia scaling, the required sliding mass would exceed the reflector mass to meet the slew requirements of a 1000 km altitude orbit. Effectively, reflectors larger than 10 m cannot be controlled via SRP, given the slew accelerations required [36].

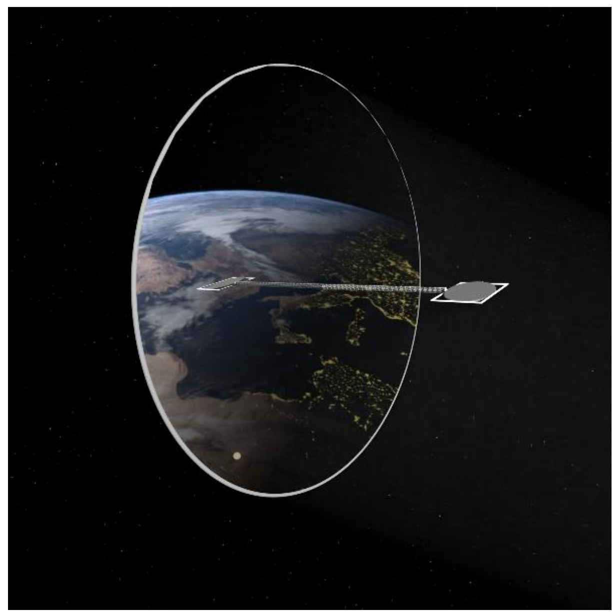

Fig. 7. Rendering of a circular reflector with two CMGs appended at the top of two booms normal to the reflector. By properly selecting the wheel mass this configuration permits the removal of the gravity gradient torques.

Alternatively large magnetic dipoles could be created by running a current loop at the edge of the reflector or using an electrically conductive support structure [37], therefore generating torques via interaction with the Earth magnetic field. However, as shown in Ref. [36], the required mass of wire would be comparable to the reflector mass, thus making this alternative again less attractive than control moment gyros. Moreover, the torque direction is affected by the direction of the local magnetic field, therefore multiple current loops with variable orientation would be required to ensure full 3-axis control.

Overall, CMGs appear to be the best actuator solution for control of large orbiting reflectors. However, additional studies are required to investigate the actuator-structure interaction, considering the structure flexibility.

Another important technical challenge in the employment of orbiting solar reflectors is therefore the reflector structure and configuration, which will be discussed in the next section.

5. Reflector Configurations

The size of the reflector does not affect the reflected image size on the Earth; however, it affects the sharpness of the image [3]. The illumination achieved is directly proportional to the ratio of reflector to image size. Hence, in order to achieve the same solar power density as daylight, the reflector area should be at least of the size of the image area. The image size is given as the product of the solar angular diameter at the Earth, which is approximately 0.01 radians, and the orbit altitude. As the image size is governed by the orbit altitude, the size requirements (for a single reflector or equivalent area of multiple smaller reflectors) are of order of kilometres.

The reflecting surface consists of an ultrathin metallic reflective coating on a thin polyimide or polyester substrate film stretched over a supporting structure [38]. In essence, these plastic materials have high strength to weight ratios. The typical aluminized Kapton/Mylar film used in such an application, has an areal density around 4 to 6 g/m^2 [4]. The support structure needs to be strong enough to sustain the forces arising from the solar radiation pressure, differential thermal expansion, gravity gradient torque and control torques [39]. The most desirable structural materials offer a combination of low weight, high strength, high vibration damping coefficients and low or zero coefficients of thermal expansion. Specifically tailored composite materials can fulfil these structural requirements. A weight restriction equivalent to 10 to 12 g/m^2 is considered for the entire structure of the orbiting reflector with the use of solar radiation pressure for orbit raising and station keeping [4].

The reflectivity properties of reflectors orbiting in medium to highly inclined near-Earth orbits are affected by interaction with the proton belt. Protons cause sputtering on the reflective surface. Low-energy protons may be trapped and produce microscopic but, in terms of the wavelength of light, sizeable bubbles of hydrogen at the interface of the plastic and its metal coating. This adds to the gradual degradation of reflectivity [6]. The degradation of reflectivity due to proton impact can be reduced or eliminated by a thicker coating than optically needed, preventing protons from reaching the interface of the metal coating and plastic. It is also desirable to provide in-situ periodic recoating of the reflector [4]. Another factor affecting reflectivity is the flatness of the reflecting surface. The support structure should provide the required flatness to maintain the desired sharpness of the reflected spot. The effect of deviation of the reflecting surface from an ideal plane geometry on the reflectivity is studied in Ref. [5]. The effect of wrinkling on the performance of reflector films is considered in Ref. [40]. Also, thermal cycling degrades mechanical and optical performances of the reflecting film [41]. The thermal stability of such kind of metal-polymer interfaces is studied in Refs. [42] and [43]. However, we expect dawn-dusk SSO to be considered and so the reflector would be continuously illuminated.

Different types of configurations employed in the past to generate such a large reflecting area include inflatable, inflatable-rigidized, petal and faceted reflector types [4]. The deployable structures proposed are designed according to the launch loads and their sizes are restricted by the size of the volumetric space available on the launch vehicle fairing [44]. Splitting of the large single reflector into the smaller reflectors, and operating in clusters, reduces the size of individual reflector and facilitates standardization [6]. In a preferred embodiment, these small reflectors can be held relative to each other in a large frame [11]. Also, building a large reflector out of smaller reflectors as modules meets the requirement for optical adaptivity.

Oberth in his pioneering work proposed to manufacture the reflector in space using the materials available from the lunar surface and asteroids [6]. The essential requirement of the vacuum for the physical vapour deposition of metals on the film is automatically satisfied in space, which is otherwise to be created for on-Earth manufacturing. Also, the defects due to packing and transporting to space are eliminated [44, 45]. In principle, components of longer length can be produced as there is zero gravity load [5]. It is anticipated that the metal required as a source material for conversion to the thin-film form could be available from a portion of the initial vehicle structure that is no longer required, such as booster tankage or interstage structural components [38].

Based on the fact conceived earlier that, faceted reflectors, i.e., those constructed of a large number of (redundant) individual tensioned plane sections, are most consistent with low mass per area, high strength and assembly in space [4], a proposed reflector design is now conceptualised. A faceted reflector of a hexagonal shape, constructed using a number of individual tensioned planes of equilateral triangles, is proposed here, as shown in Fig. 8.

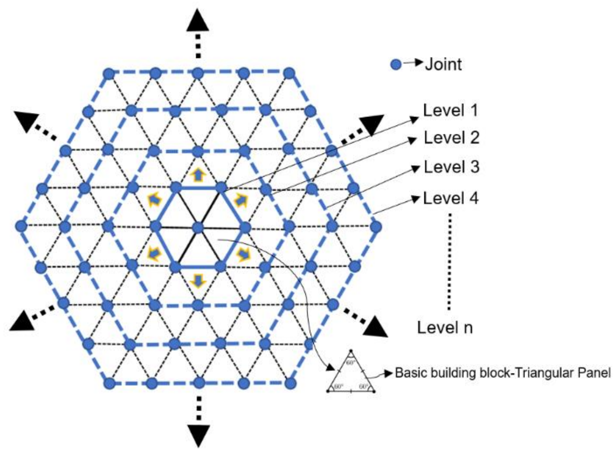

Fig. 8. Schematic of a conceptual hexagonal reflector constructed using triangular panels.

The characteristic of this design is that a reflector of any desired dimension can be constructed with the same basic building block, that is, equilateral triangles of the same size, connected through joints at the corners. These triangular panels will support the stretched reflecting film. The number of triangular panels required for any hexagon of level '*n*' shown in Fig. 8, is given by $6n^2$. Along with modularity, this design facilitates on-orbit assembly, standardized quantity production, ease of manufacturing, easy maintenance and prevents tear propagation. Most importantly, such reflectors can in principle be manufactured with present-day technology. Some of the materials that are suitable for the construction of such kinds of reflector include lightweight composites such as Carbon Fiber Reinforced Plastics (CFRP) and Graphite Fiber Reinforced Plastics (GFRP) for the main structure; and metalized ultrathin polymers such as Kapton, Mylar and CP1 for the reflecting surface. These materials will be evaluated for their performances in dedicated studies in the future.

Thus far the discussion has been limited to the technical challenges of orbiting solar reflectors. In the next section, this will be expanded to economics, including cost estimations and potential business models in a 21st century context.

6. Economic Case and Business Development Models

6.1. Simple Cost Estimate

As a case study for illustration, a constellation comprising of six 1 km diameter reflectors with a 20-year lifetime is considered. Each reflector weighs approximately 7860 kg and is placed in low Earth orbit. A simple cost estimate is made for each reflector considering a procurement cost of 375 $/kg [†], maintenance cost of 5.63 $/kg (inspired by values used in [10]) and different possible launch costs.

The current launch cost for the Falcon Heavy launcher is $1400 per kg [46]. However, with the Starship reusable launcher, it is anticipated that this cost could in principle fall to as low as approximately $10 per kg [47]. Using these values, a simply cost estimate is presented in Table 1 below.

Table 1: Cost Estimates in millions ($)

Cost item	Falcon Heavy	Starship (Optimistic)
Constellation	17.69	17.69
Launch	66.02	0.47
Lifetime Maintenance (Undiscounted)	5.31	5.31
TOTAL	**89.02**	**23.47**

The procurement and installation cost of these reflectors is significant, for the constellation of six reflectors considered, the cost varies between $89.02M and $23.47M for the most expensive to the least launch cost considered respectively (neglecting reflector development costs).

A key advantage of orbiting solar reflectors is that it can provide additional illumination to different solar power farms and other users located in different countries and continents. This opens up opportunities for several different business models, which will be discussed next.

6.2. Business Development Models

Several ownership and funding options for orbiting reflectors are considered and discussed further, as outlined below:

i. *Country Ownership*:

The orbiting reflectors could be owned by a single country which operates them as a public service for the benefit of the country's citizens (energy generation and other uses including for illumination and agriculture). A significant number of orbiting solar reflectors (hundreds or potentially thousands) are required to deliver energy generation at a national, regional or global scale. There is very high capital cost involved in installing the reflectors. To take full advantage of the orbiting reflectors and achieve financial breakeven through energy generation, multiple solar farms need be serviced. Reflector control requirements set a minimum limit to the distance between two solar farms that can be visited in succession. In addition, the orbit ground track of the reflectors limit the number of solar farms within a country that can be

† In the literature, procurement cost values considered for reflectors have ranged between 150 $/kg [4] and 389 $/kg in Ref. [10]. The decision to use 375 $/kg as an estimate cost in this work has been informed by observed trends in the large-scale cost of essential reflector components.

realistically served with dawn/dusk illumination by the reflectors.

Given that there is a minimal possibility that multiple solar farms in a single country are optimally served with dawn and dusk illumination, cooperation across countries and continents is essential. However, the main disadvantage of ownership of the constellation by an individual country is that a long–term contract with solar power farms outside the country is essential. The political and economic justification of using taxpayers' funds to build reflectors to service other country's solar power farms needs to be made in terms of national return on investment.

ii. *Commercial Ownership by a Third-party Company*:

The global space industry is attracting growing interest across the public and private sector. Indeed, forecasts by Morgan Stanley Research indicates that by 2040, the global space economy may be worth up to $1.75 trillion [48]. Another funding and ownership option is that companies and space sector businesses build, operate and sell the additional illumination to solar power farms and other users who are on the ground track of the reflectors.

For this ownership model, the company funds the construction and deployment of the orbiting reflectors, and its revenue is obtained from the fees paid (for example a fixed amount) by solar power farms and other users. The key advantage of this business model is that it generates a predictable income for the company. There is also no political restriction on the solar farms that can be serviced. In addition, it can facilitate the siting of future solar power farms along the orbit ground track of a reflector constellation.

iii. *Company Ownership Consortium*:

The reflectors could also be jointly built and owned by a group of consortium members such as solar power farm owners and nation states. The orbit ground track is then optimized to ensure that the members of the consortium of solar power farms are provided with illumination at dawn/dusk hours for energy production.

While the capital and operating costs for the reflectors are jointly paid by the consortium members, each consortium solar power farm handles the revenue earned from the additional energy sold in the electricity market. This gives a higher profit for the solar power farms compared to the case where the reflector is owned by a third party.

Long term commitment from each member is clearly essential for the consortium to operate effectively. An analysis of the ease and impact (both technical and economic) of contracting new (future) solar power farms and other potential users to be serviced by the reflector will be essential to understand the full prospects of this ownership model. Historical models such as INTELSAT, EUTELSAT and INMARSAT can provide useful insights.

Whichever business model is to be adopted, the presence of orbiting solar reflectors will bring additional regulatory issues in space or ground. Some of those challenges are identified and discussed in the next section.

7. Regulatory Issues

Given the large dimensions of the reflectors and their usage, issues related to end-of-life disposal, impact with debris and stray light will need to be addressed.

Firstly, according to the relevant guidelines on space debris, the reflector should be safely disposed within 25 years of mission completion. Possible disposal scenarios include controlled re-entry into the atmosphere or orbit altitude raising. The first scenario is usually preferred for satellites in LEO, as anticipated in this case. Due to the large area-to-mass ratio of the reflectors, the reflectors would be subjected to large drag forces which may facilitate the de-orbiting process by means of atmospheric re-entry. Alternatively, solar radiation pressure may be exploited to increase the semi-major axis of the orbit to reach a safe graveyard orbit, such as the one beyond the GEO altitude. A preliminary estimate using Eq. 13 from Ref. [7], suggests that an orbit raising manoeuvre to GEO exploiting SRP would take approximately 220 days, i.e., well within the recommended 25-year period. However, given the advantage of the large drag available, a controlled atmospheric re-entry could be more appropriate. Detailed analyses will be needed to assess the feasibility of this scenario, considering the specific structural design of the reflector.

Another issue related to the large area of the reflector is the risk of impact with space debris. A potential collision between the reflector and a small cm-scale object may be catastrophic and increase the orbit debris population, although impact with the membrane is likely to be benign. This risk is clearly augmented in a constellation with multiple reflectors. It is believed that the risk of collision at orbit altitudes between 900 and 1000 km will increase over the coming decades unless some form of active debris removal will take place. It is therefore apparent that the reflectors may occasionally undergo impacts. If an impact is estimated with an object whose orbital elements are known, a debris avoidance manoeuvre could be scheduled in advance when necessary. Use of SRP could be beneficial in this case to temporarily change the orbit altitude. A constellation of smaller more agile reflectors with the ability to self-organise would further reduce the risk of impact.

Environmental issues associated with stray light should also be considered. Sunlight may be reflected to undesired regions during reorientation manoeuvres, possibly disturbing populated areas or in general increasing light pollution, thus hindering astronomic observations. Such issues may be partially avoided by carefully planning the reorientation manoeuvres in order to avoid targeting unwanted areas. At the end of a tracking phase, the reflector could also be rotated into an idle mode, i.e., edge-on configuration with the reflector normal at a 90 deg angle with respect to sunlight, such that no light reflection occurs.

Other studies, e.g., in Ref. [7], also outlined the possible ecological impact of illumination from space, in relation to its adverse effects on wildlife in general. However, potential adverse effects would be more likely in case of full-time illumination, whereas in this case the illumination is temporary. Moreover, it should be noted that the level of illumination on the ground for a 1 km structure generating a 10 km ground spot is substantially lower than the standard daylight illumination level.

Recently it also became evident that astronomical observations are disrupted due to large-scale constellations. This was mostly discussed in the context of the Starlink internet constellation, in which approximately 1700 satellites are operated currently by SpaceX[‡]. The current number of satellites is only a fraction of planned number of satellites, which is on the order of 42,000 in total [49]. The International Astronomical Union and American Astronomical Society, as well as individual astronomers have raised concerns on the impact of the Starlink constellation satellites [50, 51], which make frequent passes over given regions for coverage reasons. Similar issues may be raised for orbiting solar reflectors, which, given the potentially large size of the reflectors, may have a similar impact as the Starlink constellation. However, by an appropriate scheduling of the reflectors, as well as through the idle mode described earlier, this can in principle be avoided. Moreover, it is likely that high-altitude locations (e.g., mountain tops) favoured by astronomical observatories are not *always* favourable for solar power farms due to accessibility. In addition, the targeted dawn/dusk times for passes over solar power farms are still substantially illuminated for night sky observations, therefore only a limited overlap is anticipated.

It is clear that regulatory issues should be considered from the very beginning of the development process. However, the extent of the impact and public perception on their deployment can be best understood while the technology for orbiting solar reflectors is being demonstrated. In the next section, an integrated technology demonstration roadmap is presented in order to achieve full commercial deployment of the system.

8. Technology Demonstration Roadmap

In order to achieve successful full-scale deployment of the reflectors for terrestrial solar energy applications, some of the key aspects of the proposed concept needs to be demonstrated in order to increase the technology readiness level (TRL) of the concept in the near term. Figure 9 below shows the technology demonstration roadmap discussed here.

The first step is the laboratory demonstration of key aspects of the reflector technology. This includes manufacturing the reflector membrane and its supporting structure, deployment of the scaled reflector subsystems in vacuum and measurement of key properties of the reflectors, such as reflectivity, wrinkling and degradation under thermal and structural loads that the reflector will encounter in space.

Once a level of confidence is achieved for the reflector and its deployment system in a laboratory environment, it can be demonstrated using sounding rocket flights and high-altitude balloons. Sounding rockets can reach altitudes as high as 700 km and provide a free-fall opportunity for 10-20 min. Deployment of a single small reflector of a size potentially up to 20 m may therefore be tested in the space environment. In an ideal dawn/dusk launch, the test system may include attitude control capability, which would allow a demonstration of the deployment of the reflector, orientation of the system and reflection of sunlight back to the Earth while in free-fall, within which light intensity can be measured by a sensor system on ground. At 700 km, the image of the solar disk on ground would be approximately 7 km diameter. In principle, as long as the observer is within that circle, reflected sunlight intensity will be measurable.

Reflected sunlight may also be captured by a high-altitude balloon flight. High altitude balloons do not cross the boundary of space but often can reach altitudes higher than 50 km but stay much longer (generally 2-3 hours) in contrast to sounding rockets. In this case, a small reflector attached to the balloon gondola and a dawn/dusk balloon launch may be considered. It is likely that a level of control will be necessary to reflect the sunlight to the ground site, but long duration flight means that the reflected solar image may be observed at different elevations as the balloon drifts. This would allow understanding the efficiency of the reflector at low elevations.

[‡] This information is obtained from "Starlink Statistics", Available at https://planet4589.org/space/stats/star/starstats.html (Accessed 10 September 2021)

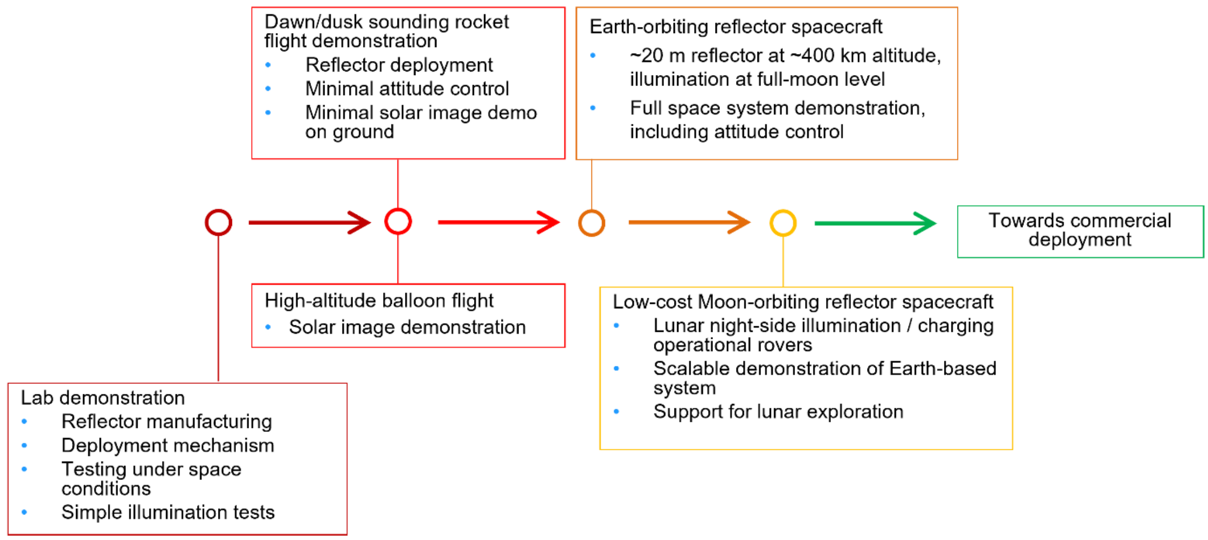

Fig. 9. Envisaged solar reflector technology roadmap

Further technology demonstration can be achieved in orbit. A small satellite may be considered as the representation of the full-scale system. A mission of this kind can reproduce the reflector spacecraft at a smaller scale with its deployment, control and operation. The reflector satellite may be deployed in an orbit altitude below the ISS (i.e., below 400 km). At this altitude, the orbital pass would last approximately 10 min, during which light intensity on ground would reach higher than full-moon intensity for more than 3 min with a 20 m reflector, and nearly the entire pass duration for a 100 m reflector, as shown in Fig. 10. Light intensity of this magnitude should be visible at suitable locations on the Earth. Alternatively, the image of the solar disk may be reflected on clouds and images may be taken by an Earth observation satellite or the astronauts on the ISS. The large atmospheric drag at this altitude would also result in the reflector satellite deorbiting in a few weeks without generating additional space debris.

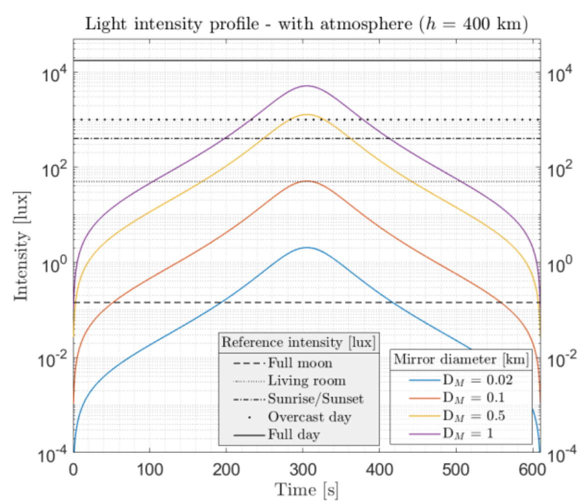

Fig. 10. Light intensity profile during an orbital pass at a 400-km altitude circular polar orbit around the Earth.

A potentially interesting technology demonstration mission may also be considered around the Moon. The reflector could in principle be deployed near the Earth and used as a solar sail to reach the desired orbit around the Moon, or it could be a piggy-back payload on a future lunar mission. Such missions may have multiple advantages. The absence of a lunar atmosphere means much higher illumination levels on ground with smaller reflectors, allowing a test of the illumination achieved by large reflectors around the Earth with smaller ones around the Moon [52]. The level of illumination on ground can be measured through solar panels of operational lunar rovers or the solar image could be imaged from lunar orbit. Moreover, energy supply may be a more immediate problem on the lunar surface with growing interest on a permanent presence on the Moon. A technology demonstration mission around the Moon may therefore be an opportunity to showcase the potential of the concept of orbiting solar reflectors on the Moon for terrestrial applications, or to support lunar operations. These include illumination to support human or robotic operations, or direct energy delivery. This may also enable public acceptance as demonstrated through lunar applications.

The proposed technology demonstration roadmap is in principle achievable with currently available technology and would pave the way for a full-scale commercial service in future.

9. Conclusions

This paper has discussed the technological challenges and opportunities, economic aspects and regulatory issues associated with the successful employment of orbiting solar reflectors.

Even though the Sun is a virtually endless source of energy, terrestrial solar energy capacity is only limited to daylight hours and cannot supply the demand in critical hours of the day, e.g., dawn and dusk without storage. It was argued that there is a timely opportunity in the employment of orbiting solar reflectors to offset such deficits in these critical hours, due to growing demand for global clean energy services and thanks to falling launch costs through reusability, growing payload capacity and recent developments in on-orbit manufacturing.

A constellation of orbiting solar reflectors using families of Sun-synchronous orbits are well suited to providing opportunities to reflect additional sunlight to terrestrial solar power farms. Moreover, attitude control demands can be best delivered using control moment gyros. Similarly, a novel modular hexagonal reflector structure is also proposed for ease of manufacturing and maintenance and standardization.

A simplified analysis shows economic viability when falling launch costs are considered for an illustrative case study of a six-reflector constellation. Alternative business models are available for operations, each with their own advantages in terms of business economics. Regulatory issues due to orbiting reflectors have addressed with potential solutions to each. Finally, a technology demonstration roadmap has been presented, connecting current technologies to future large-scale commercial operations.

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