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CAN WE COOL THE EARTH?

Space Mirrors

Review of a Futuristic Geo-Engineering Technique

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Abstract

Climate change is the greatest crisis that mankind has ever been in as its effects will be unprecedented and might result in apocalyptic scenarios. Geoengineering can be used to save time to switch to green energy and to offset the effects of climate change in general. The aim of this report is to locate the use of space mirrors in the climate change crisis. Space Mirrors is a geoengineering technique, that relies on the fact that deflecting about 1.8% of the total incoming sunlight on Earth could offset a 2 °C temperature increase. Two promising concepts were selected to investigate in this report with the aim to locate the role of the technique of space mirrors in the field of geoengineering: the cloud and the ring concepts. The cloud idea consists of putting small flyers at the Lagrange point L1 to deflect the incoming sunlight, while the ring concept consists of forming rings, as the ones of Saturn, from captured asteroid particles in the same goal. Both techniques are analysed as a way to delay climate change. The role of space mirrors was found to be a last resort technology. It is one of the most expensive options but is guaranteed to work if implemented correctly, therefore, it should be implemented if it is known that the tipping point of Earth's climate is about to be reached. The cloud concept shall be selected if space mirrors are to be used as it relies less on far stretched technologies and is less expensive. The technique also needs to be used along other methods such as carbon capture and the transition to green energy. Further research in the technique on space mirrors should focus on it's local effects and cost-reduction methods.

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1 Introduction

It is now obvious that the human activities have an impact on Earth's climate, causing the entire planet to heat up. In comparison to the average pre-industrial temperature from 1880, the overall temperature rise has been estimated to be a little more than 1 °C [1]. This temperature rise is explained by the large emissions of heat-trapping gases (or greenhouse gasses) from mankind such as carbon dioxide, nitrous oxide, methane, ozone, and multiple chlorofluorocarbons. The most critical greenhouse gas being carbon dioxide as it has a larger impact on the climate than the others, acting on the heat balance as a one-way screen [2]. According to [3], at present humans are releasing around 9.5 billion metric tons of carbon into the atmosphere each year due to the common use of fossil fuels, while another 1.5 billion metric tons are put in the atmosphere through deforestation and other land cover changes. Some of those emissions are absorbed each year by natural cycles of vegetation (3.2 billion) and oceans (2.5 billion). Meaning that a net additional 5.3 billion metric tons of carbon remains in the atmosphere each year. This means that since 1750, humans have increased the amount of CO_2 in the atmosphere by about 50% [3]. This results in changes of the climate on a global level which is the primary cause for multiple changes on the planet such as the increase in natural disasters, the rise of sea level and athe increase of the temperature on earth.

Climate change is the next large scale crisis that mankind will have to deal with and three paths can be taken to overcome it: mitigation, adaptation and geoengineering [4]. This report considers a geoengineering technique as a way to fight against climate change, although the two first paths shall be taken in parallel for a sustainable future. The most widely accepted definition of geoengineering is that geoengineering is "the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change" [5]. Climate geoengineering can be done in many forms, however most techniques fall into either one of two categories: greenhouse gas removal or Sunlight Radiation Management (SRM). Space mirrors are a part of this second category and are specifically an albedo modification technique. In other words, space mirrors are theoretically designed to change the overall reflectiveness of the earth for sunlight. The technique is therefore not a solution to the greenhouse gas effect and can only be used to change the temperature on Earth, in order to have enough time to come up with a solution to the underlying problem. This report aims to assess the role of space mirrors in climate geoengineering and determine what concept would be the most appropriate considering their feasibility, risks and benefits.

The report is structured as follows. First, chapter 2 provides an overview of the concept of space mirrors the history of the technique and its working principle to an assessment of its reversibility. Then, the expected positive and negative effects are discussed in chapter 3 with an emphasis on the possible risks of the method, including an analysis of the reversibility of the technique. A discussion of the feasibility of the technique and the ethics around it is then provided in chapter 4 combined with a comparison to other well-established geoengineering proposals. Finally, chapter 5 provides some conclusions and recommendations for further research on the topic.

2 Concept Overview

This chapter provides an overview of the concept of Space Mirrors. First, section 2.1 presents a brief description of the evolution of the concept throughout the years. Then, section 2.2 gives an overview of the general implementation, considering two concepts for space mirrors: the cloud concept and the ring concept.

2.1 History

The idea of space mirrors (or space sunshades) in orbit around Earth was first introduced in the 1980's in the form of theoretical work to cool Venus. The idea relied on the ambition to terraform the planet to make it possible for life [6]. Another similar application of mirrors in space is the possibility to use them to concentrate light in particular places on Earth. This would boost the economy of solar energy, making it possible to produce energy during the night and in larger amounts as well. This report is focused on the use of space mirrors to cope with climate change and will therefore not expand further on the topic of solar energy generation. Having said that, the essential workings of space mirrors have remained the same throughout history: Modifying the sunlight radiation that reaches a planet. The exact details of the implementation have however changed throughout history.

In 1992 [7] proposed an array of mirrors at Lagrange point 1. The proposal was based on the assumption that a decrease of 0.5% of the sunlight radiation that reaches Earth's surface is sufficient to halve the effect of a CO_2 doubling [8]. It was calculated that an estimated 55000 space mirrors with a surface area of 10^8 m^2 each was needed if these space mirrors were the only geoengineering solution that is used to cool down the temperature on Earth [7]. This does seem like a very unrealistic engineering task, however this scenario was based on the assumption that space mirrors are the only geoengineering solution available, which is most likely not a realistic scenario in itself.

One of the first concrete concepts was suggested by Gregory Benford in 2004. His idea was to put a 1000x1000 km Fresnel lens that is only a few millimeters thick at the Lagrange point L1 of Earth. The amount of sunlight reaching Earth would then be reduced by a few percents, effectively cooling the planet by affecting the heat balance. Benford estimated that the total cost of such approach would be of around 20 billion $ (FY2005) and that it could be done using the current technology available [9]. It is noted though that the estimated cost is most likely far off due to the technological challenges presented by such structures. It would most likely also require to be built in space due to the huge size it represents. This idea is illustrated by Figure 2.1.

The two leading proposals right now are the spacecraft / particle cloud concept and the ring concept. These two will be investigated further in the context of this report.

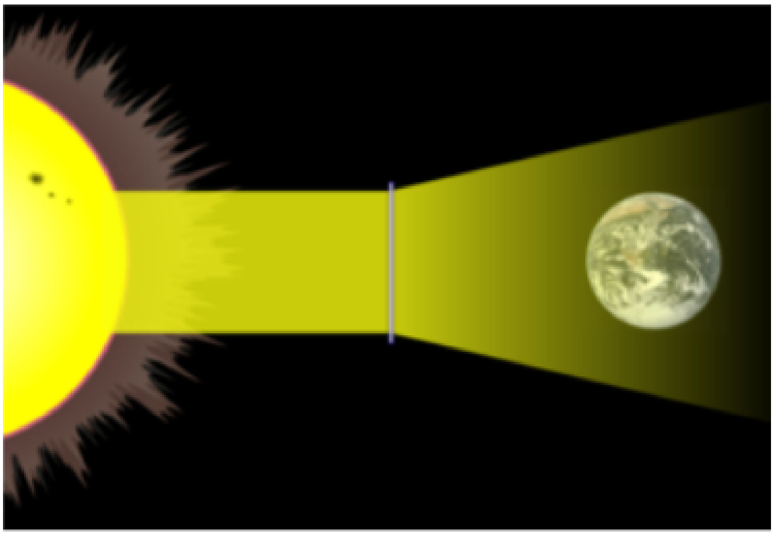


Figure 2.1: Schematic representation of the Fresnel lens concept as proposed by Gregory Benford.

2.2 Implementation

This section presents an overview of the implementation of the two leading space mirror proposals in literature: the cloud concept and the ring concept. These techniques will be analysed with the purpose of giving a thorough background on these concepts in order to be able to draw conclusions about them in a later stage of the report.

2.2.1 Cloud Concept

The cloud concept presented by [10] consists of trillions of small spacecrafts made of transparent material placed at the Lagrange point (L1) between the Earth and the Sun. The primary role of this material in orbit is to deflect 1.8% of the sunlight just enough such that it misses the Earth. Deflecting the sunlight rather than completely absorbing with the spacecrafts would mean that the resulting solar pressure force would be significantly less and therefore less aggressive solar control would be required for the stability of such a configuration.

Structure of the Cloud

Two main configurations can be envisioned: a random set of small flyers or a packed, tightly controlled set of those. In both configurations, two main types of spacecrafts are considered: the flyers and larger GPS-like spacecrafts. The flyers are largely dominant as they are the ones deflecting the sunlight, while the GPS-like (larger) spacecrafts are present to make sure that no collision occurs between the flyers.

Figure 2.2 shows a preliminary design of the flyers from [10], where a disk like shape of 1 m diameter and a few millimeters thick for a total mass per flyer of 0.1 g and a lifetime of about 50 years in total was proposed. The use of small flyers instead of one large Fresnel lens (as suggested by Gregory Benford [9]) removes the need for in-space manufacturing and/or assembly as they can all be manufactured on Earth and launched separately to the required position. The flyers would be made of a transparent film pierced with tiny holes to deflect light.

Furthermore, it can also be seen in Figure 2.2 that the flyers have three 100 μm thick tabs containing all the required electronic devices such as radio transceivers to communicate with the GPS spacecrafts, solar sails for active attitude control, tracker cameras for attitude determination using the Sun and the Earth positions, and solar cells for power generation. The solar sails would benefit from the constant solar pressure on the spacecraft to modulate it to keep the flyer in position with a correct attitude, removing the need for any propellant or costly alternative for active attitude control.

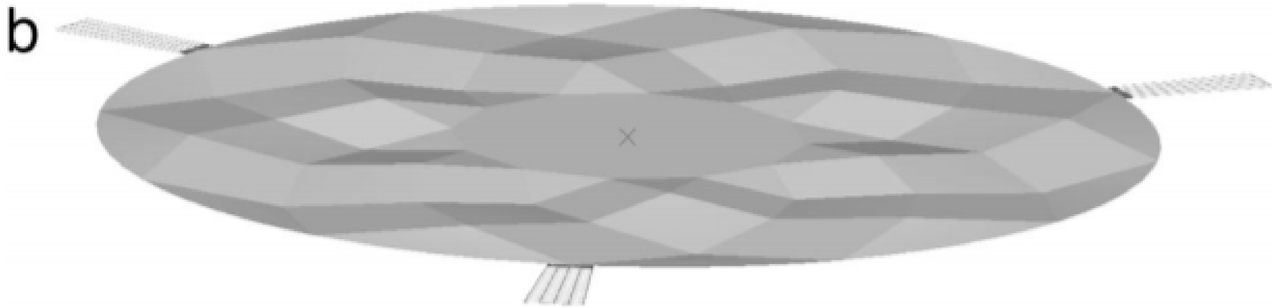


Figure 2.2: Preliminary flyer design as proposed by [10]

Given that the amount of spacecrafts required would reach trillions, having full control of the distributed system is not deemed possible and therefore a random cloud is believed to be more realistic. Such a random cloud would require to have an elliptic cross-section comparable to that of the Earth (6200 x 7200 km)[1] and a length of about 100,000 km. Such a large length is necessary to avoid the risk of many collisions occurring between the flyers because of an unexpected event.

The total mass of the cloud has been estimated by [10] to be about 23 million metric tons, although this could be reduced as small flyers require lighter structural parts than larger spacecrafts.

Positioning of the Cloud

The Lagrange point (L1) is a point at about 1.5 million kilometers from Earth on the Earth-Sun line. The Lagrange points of two bodies in space are such that any small object positioned at this exact location will remain at this relative position as the system evolves. This is explained by the fact that the exact centripetal force required for a small object at this position to stay in orbit is precisely equal to the gravitational pull of the two large masses (Sun and Earth in this case). In total, five of such points are present for a three body system, this is illustrated by Figure 2.3 for the case of the Earth-Sun system.

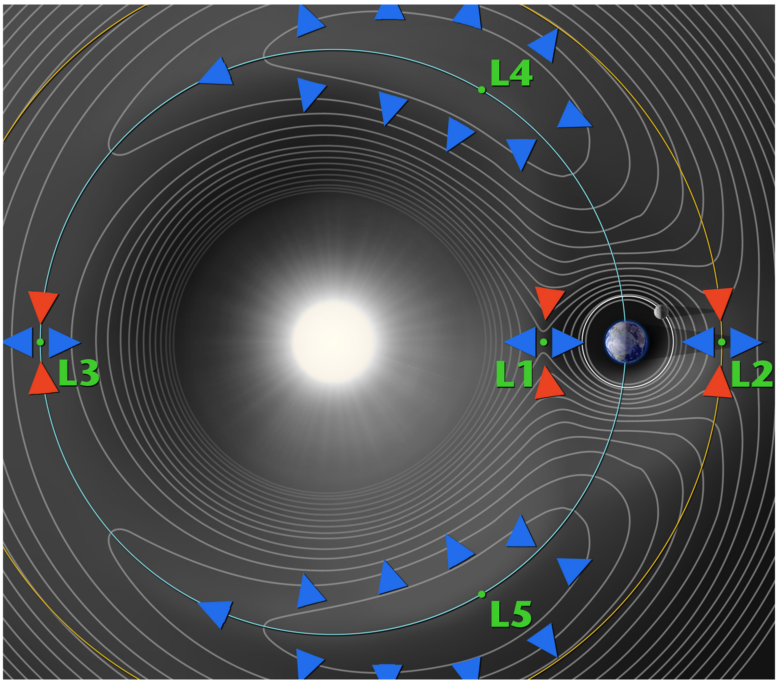


Figure 2.3: Lagrange points of the Earth-Sun system [11]

[1] Note that the packed version would require a 7.6 times smaller cross section. The total mass would also be significantly less.

It can be seen in Figure 2.3 that the L1 point is such that placing a cloud of mirrors at this position, should make it stay between the Earth and the Sun at all times. For this very reason, the L1 point is the preferred location for most space-based geoengineering techniques. However, L1 is a saddle point in the gravitational potential, meaning that it is fundamentally unstable [11]. In the case of a cloud of small spacecrafts, the cloud would be dispersing in a few months if no active control is used. A cheap way to maintain the life-time of such system for a few decades would be by modulation of the solar pressure acting on it as it would not require any additional propellant.

Launch

Most other studies, such as presented in subsection 2.2.2, envision the manufacturing in space to limit launch costs. However, this is still part of science-fiction and therefore the mission considered here assumes a manufacturing process that is Earth-based. This requires a very low cost launch which can be made possible by the use of an electromagnetic (EM) launcher. Although EM launchers have not yet been used in practice, they are under constant consideration and could be used for cheap transportation of small amounts of payload at a time to Low Earth Orbit (LEO) in the future.

EM launchers operate like a gun, giving the nearly complete ΔV at the launch pad and the payload travels the atmosphere in a capsule like a bullet until reaching LEO. Figure 2.4 presents the concept of electromagnetic launcher.

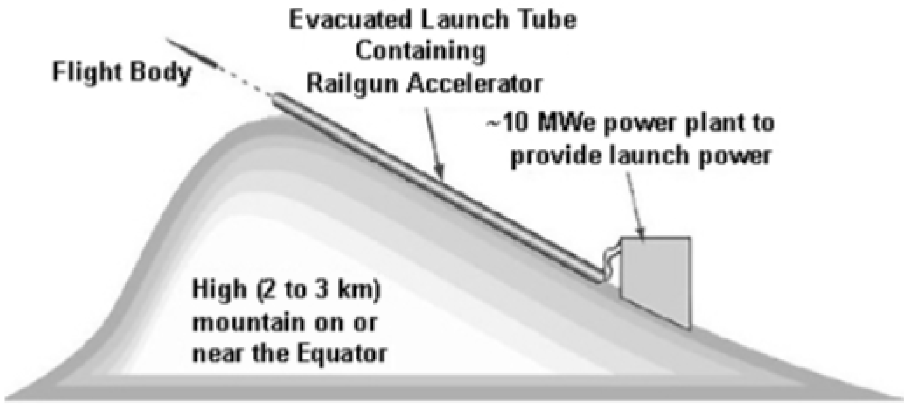


Figure 2.4: Electromagnetic launcher concept as presented by [12]

Electromagnetic launchers are not yet ready to compete with advanced conventional technology but with enough funding, this could become reality [12]. As the launch vehicle gets out of Earth's gravity, ion propulsion can then be used as it adds only small mass and is relatively cheap [10]. A total cost of 50 $/kg is deemed realistic for large amounts of payload (20 million tons in total), by considering the energy necessary to launch a payload to orbit and comparing it to the price of electricity. [10] argued that the kinetic energy at escape velocity is around 63 MJ/kg and used a factor of ten for the margin of error taking into account the mass of the launch armature, the ion-propulsion fuel and efficiency of conversion. The cost of electricity being of a few cents per kWh, the launch energy cost would come to about 9$/kg. 50$/kg is believed to be reasonable taking into account the storage and transportation for large amount of payloads.

2.2.2 Ring Concept

[13, 14] suggested another approach inspired by the rings of Saturn. Artificial rings around Earth's equator could be formed with either particles or spacecrafts, that would partly block the sunlight reaching Earth's surface. From the proposal it becomes clear that the particle variant is a more feasible option, so this is the scenario that will be further analysed.

The ring concept was first introduced by [14], where the brought concept was discussed and worked out on a working principle level. The idea as presented in this first report was to construct a Saturn-like particle ring around the Earth between $1.2R_E$ and $1.6R_E$ (R_E is the Earth's radius). [13] further analysed this concept by mostly improving the analytical models for the orbital dynamics by for example taking the J_2 perturbations of the gravitational force of the Earth [2] into account and by using a 3D model instead of the 1D model used in [14]. The scale of the dust particles that are used in the ring concept ($10\ \mu m$) make normally insignificant effects such as J_2 perturbations very important for the stability of the ring, which is a very important parameter for the implementation of this concept. Furthermore, [13] improved the analysis of other interesting aspects of the concept such as the origin of the dust particles and the seasonal dependence of the ring effects, which will also be discussed in this section.

Origin of materials

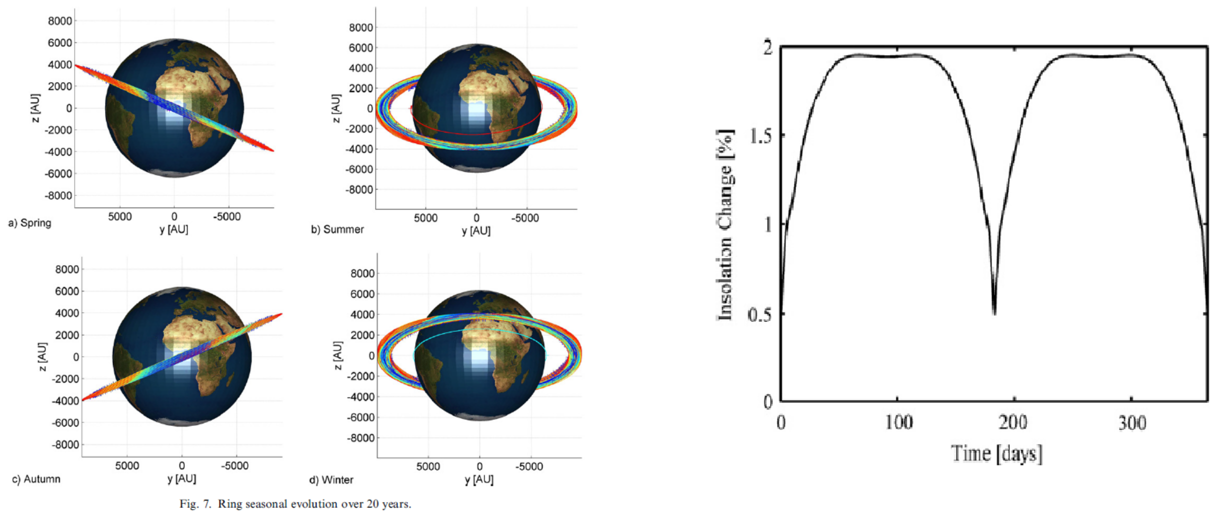
An important aspect of this concept is the origin of the particles. [13] proposes the use of asteroid particles. This suggestion is very important, since the use of Earth's dust grain particles would imply that masses of the order of 10^{12} kg would have to be launched into orbit. This is not feasible with the current launching technology. Using asteroid particles that are already lifted into space works around this problem. The exact idea is the following. Machines can harvest asteroid dust grain particles with a determined interval of radii. The harvested grain particles can then be given a velocity Δv in a specified direction, such that they reach the feeder orbit. From there, they will spread over the full ring due to their different mass-to-area ratios. The mass needed to reduce the solar radiation on Earth's surface by a given percentage is however highly dependant on the precision of the farming mechanism ([13] only considers 3 normally distributed particle size distributions with different standard deviations). So further research in this feature is much needed, as perfectly sized asteroid particles can never be formed.

Seasonal dependence of insulation

An important consequence of this concept is that the effective area of the ring tangent to the Sun changes over the course of a year because of the rotation of the earth's axis relative to the sun during a year (see figure 2.5a). This means that the insulation is dependent on the specific season. This dependency is illustrated in figure 2.5b, where the insulation (so sun-blocking efficiency) is plotted against the days of the year. It turns out that the insulation drops significantly during spring and autumn compared to the other seasons. This means that the ring concept will actually decrease seasonal temperature differences and thus make the seasons more modest overall.

The average insulation that is required to offset a 2 $°C$ increase in temperature is estimated to be 1.7% by [15]. [13] has calculated that an accumulated mass of the order of about 10^{12} kg is necessary to accomplish this average insulation of 1.7%. This mass estimation is again highly dependent on other parameters such as the spread of dust size radii, exact position of the ring and exact composition of the dust particles.

[2] J_2 perturbations are disturbances in the gravitational force of the Earth due to the fact that the Earth is not a perfect sphere.



(a) (b)

Figure 2.5: Figure (a) shows the reason for the seasonal dependency of the sun-blocking efficiency, (b) shows the sunlight blocking efficiency during an entire year and it's dependency on the specific season. [13]

Economics

An important measure of the feasibility of this technique is the associated costs. Unfortunately, the report of [13] does not include a discussion about the costs of it's proposal. However, [16] has calculated that an asteroid mining based technique would have costs of about \$25 per kg of material. Since [13] calculated that a mass of about 10^{12} kg is necessary, these total costs become \$25 trillion. [13] estimates that most mining efforts to accumulate to the mass of 10^{12} kg will be in the first 10 years. So then the annual costs of the technique would be \$2.5 trillion or 3.1 % of the world GDP. Note however, that this calculation was made in 1989, so a new estimation would most likely result in significantly lower costs.

Effects and Risks of the Method 3

In this chapter, the different possible positive and negative effects of the method on the climate are presented. The potential benefits are presented in section 3.1 and the main risks or problems with the geoengineering technique are explained in section 3.2. Finally, an analysis of the reversibility of this method is given in section 3.3.

3.1 Benefits

This section discusses the benefits of using a space mirror method as a geoengineering solution to climate change. The benefits are divided in benefits compared to another popular geoengineering solution: Stratospheric Aerosol Injection, the benefits of the working principle, the benefits of the side effects and the long-term benefits of a space mirror solution. General benefits such as 'decreasing the temperature on Earth' or 'giving time to solve the problem of excessive greenhouse gasses' are not mentioned in this section because they are seen as a criteria for any geoengineering solution.

3.1.1 Benefits compared to Stratospheric Aerosol Injection

Compared to Stratospheric Aerosol Injection (SAI) [1], one of the leading options in geoengineering, it is beneficial that space mirrors do not inject particles in ambient air. There are concerns that SAI could lead delay recovery of the ozone layer in the artic by between thirty and seventy years. This is still controversial; other researchers believe the damage would only be 'modest' [17]. Additionally, SAI would lead to an about 14 percent increase of sulfate emission, this could have serious health effects and could potentially threaten ecosystems [17], Space mirrors do not have these kind of risks. It is beneficial that space mirrors do not suffer from these kinds of side effects.

3.1.2 Benefits in working principle

Space mirror solutions have another big benefit: they are expected to have a short adaptation time once deployed. It is expected that the cooling effects of space mirrors will already be felt within the first few years [17]. Given that geoengineering will probably have a high urgency in the near future, a solution will only suffice if it can act within a short time span. This short adaptation time also means that possible undesired side effects will be noticed early in the implementation, which means that it will be easier to 'pull the plug' if that necessary for a space mirror solution compared to other geoengineering solutions.

[1] SAI is a category of geoengineering techniques that use the cooling effect of injection aerosol (sulphur often) particles into the air to reduce the temperature on Earth.

3.1.3 Side effects

Proponents of space mirrors also argue that space-based systems would have less significant and more predictable side effects than other geoengineering options [17]. It is however hard to compare side effects of a general space mirror solution, since each implementation has drastically different side effects.

A side effect that is predicted for a space mirror solution is the following. [14] predicted that that the so-called harmful Van Allen radiation belts [2] around Earth will decrease in size. This might lead to better satellite communication, which would for example increase the efficiency of international communication and GPS system accuracies.

3.1.4 Long term benefits

A big benefit of a space mirror geoengineering solution is the fact that the space-based systems often have expected lifetimes of around 50 years. This means that once the main challenge of installing such a solution is resolved, the benefits will last for a long time. Since it is expected that a lot of time is needed to solve the problem of excessive greenhouse gasses in the atmosphere, a long term solution is definitely a necessity for any geoengineering solution.

Another benefit that will only become apparent for very large time scales is the fact that the space mirror solution could be configured in such a way to use the reflected sunlight radiation for energy to be used on Earth [18]. This is however still an engineering challenge that can not yet be solved with current technology.

3.2 Risks and Problems of the Method

Implementing any form of geoengineering introduces many risks for different stakeholders. The implementation of such large scale projects can never be perfectly modelled and therefore some unexpected consequences can always arise and cause great troubles in the future. In this section, the most significant risks of the space mirrors will be analysed to the extent of which they are currently known.

3.2.1 Local effects

The effect of a general sun-blocking technique on a local scale are quite important to be understood and can form a huge risk when overlooked. Unfortunately, the local effects are also very difficult to predict and can only be estimated. Such an estimation was done by [19]. The results of this research can be seen in the maps of Figure 3.1, which show the relative temperature changes (Figure 3.1a), the ice depth change (Figure 3.1b) and the precipitation change (3.1c) for a situation where the amount of solar radiation reaching the Earth is artificially modified to be lower.

Figure 3.1 clearly show that the local effects of a space mirror technique are very significant. Figure 3.1a shows that some regions near the poles will become relatively warmer, whilst temperatures above the oceans will decrease slightly compared to the average temperature on Earth in this situation. This is an unwanted consequence as ice melting near the poles (which can also be seen in Figure 3.1b) may lead to a rise of the sea level, which is one of the actual consequences of climate change that this technique tries to prevent.

Moreover, figure 3.1c shows that precipitation in regions near the equator will decrease significantly. These regions are often very dry regions already, so an even further decrease in precipitations in these regions is a very high risk and might lead to less valuable crop land in these regions and unfortunately also to more death due to a lack of drinking water and food in these regions.

[2] Van Allen radiation belts are belts of charged particles around Earth that are trapped in Earth's magnetic field. These charged particle belts can cause hazards for space missions.

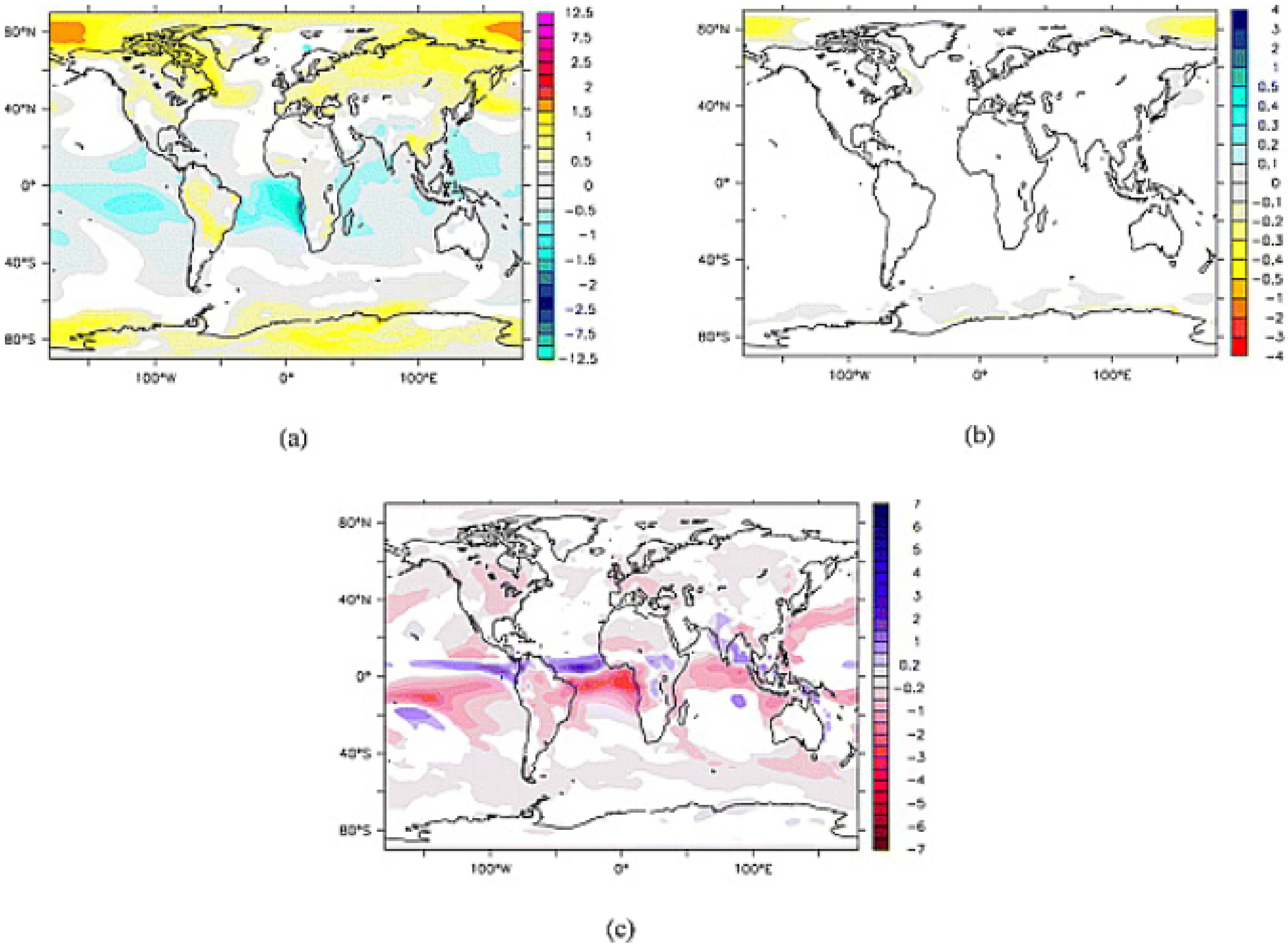


Figure 3.1: Map with the local effects of a general sun-blocking geoengineering solution. (a) shows the change in air temperature at a height of 2 metres in °C, (b) shows the change in sea ice depth in metres and (c) shows the change in precipitation in mm/day. [19]

It should however be noted that these effects are for a very specific case of a sun-blocking technique and can not simply be taken as true for space mirror techniques or even more specifically for the cloud and ring concept. The exact local effects for these concepts have not yet been researched, however the research done by [19] does show that the local effects of these two techniques can be quite significant and should definitely be thoroughly researched before implementation.

[20] has however shown that local effects of general sun-blocking techniques can be counteracted by a spatial pattern in the sun-blocking efficiency. The trade-off of such a proposal is however that the overall insulation is decreased or that more material is needed to reach a certain insulation compared to a homogeneous sun-blocking efficiency. Moreover, since the uncertainties in the local effects are quite high, the uncertainties in the exact pattern that is needed are also very high.

Concluding, a lot of research and simulation is necessary to be able to characterize and possibly counteract the local effects of a sun-blocking technique such as space mirrors. It is however clear that local effects of such a technique are most likely very significant and should thus be well-defined before proceeding with any form of implementation.

3.2.2 Response of World Leaders

Many of the risks that are associated with space mirrors are shared with other forms of geoengineering. An issue raised in contemplating the prospect of geoengineering in general is that it might cause 'moral hazard'. The general idea is that people will do less to mitigate climate change, if geoengineering is an option. This is a complex issue with multiple sides. It has also been suggested ([21]) that geoengineering might encourage governments to do more to reduce CO_2 emissions, as policy makers would get 'a sense of urgency' when they have to make policy for such a geoengineering solution. This does however most likely not outweigh the risk of moral hazards by these governments.

This risk of moral hazard is quite unpredictable and comes along any geoengineering technique. Although in this case, space mirror concepts only act on the heat balance of Earth and therefore only serve to decrease the overall global temperature on the long term. This means that other effects of global warming such as the acidification of the oceans and would not stop sea level rise as climate change is a slow process and direct changes in the system do not induce direct consequences. For this reason, world leaders would probably stay aware of the issue and not assume that the problem was solved by geoengineering. But this is only extrapolation.

As described in subsection 3.2.1, the impact of space mirrors can very drastically on a local scale. The predictability of these local effects play a big role in the international cooperation for a project such as space mirrors. This is another reason to invest heavily in research on local effects of the cloud and ring concept of space mirrors. If such research shows negative consequences for some parts of the Earth (which will most likely be the case), then world leaders in these regions might not agree on the use of space mirrors as a geoengineering solution, which again reduces the feasibility of the implementation of space mirrors. Ultimately, conflicts around the possible implementation of space mirrors can aggravate overall international cooperation, which will be necessary for any progress in solving the problem of climate change.

3.2.3 Excessive Reflection

One of the main risks presented by this mission arises if the mirrors are effectively too reflective. A too reflective 'mirror' would not be allowing enough sunlight to reach Earth, meaning that the planet gets cooled a lot more than initially first expected. Figure 3.2 shows the temperature profile on Earth as a function of the longitudinal angle for three different decreases of the sunlight radiation that reaches Earth according to [22]. This clearly demonstrates the fact that even relatively small changes in the sunlight radiation that reaches Earth can have big impacts on the temperature on Earth.

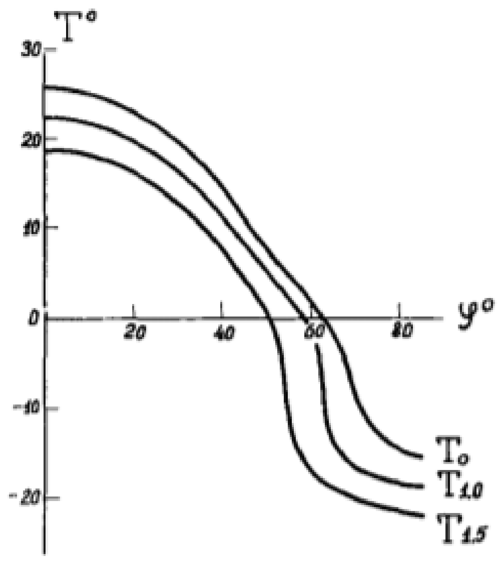


Figure 3.2: Graph that illustrates the dependence of the temperature profile over the longitudinal angle for a sunlight radiation decrease of 0%, 10% and 15%. [22]

An increase of the Earth's temperature compared to the pre-industrial norm is catastrophic as announced by climate change, but a decrease in temperature of a few degrees compared to that same reference can have equally devastating effects. Examples of such effects include famines due to crop failures and lack of reserves (which usually include about 30% of yearly production), and possible new diseases as happened in past cold long-term events [23]. Though, it is important to keep in mind that the effects of the global temperature dropping would be far less concerning than the consequences of global warming.

3.2.4 Hydrological Cycle

Like other solar radiation management techniques, space mirrors would likely lead to precipitation declines, as evaporation is about twice as sensitive to sunlight as to temperature. The reduction in evaporation could substantially weaken Asian and African Monsoons, which are vital for the food and water supplies of billions [17]. For space mirrors similar to the cloud concept, precipitation might decrease by 5 percent in the tropics, due to colder and less evaporative tropical ocean surface [17]. These space mirrors may also lead to increased precipitation "north of the equator in the Atlantic and eastern Pacific" [17].

3.2.5 Presence of the Structure and End of Life

Given the nature of the concepts presented in chapter 2, the fall of debris from the structure might be a concern. Concerning the ring concept, the current spacecrafts in orbit could be damaged or put in harm by the presence of the rings. However, the particles put in orbit are vastly negligible in comparison to the 30 million of space debris weighting about 1 g already present in LEO [10] and possibly harming the current spacecrafts. Therefore, the concept does not bring any additional concern on this level.

For both the ring and cloud concepts, an end of life can be reached, meaning that some flyers or particles could fall back directly on Earth. However, this is again probably negligible compared to the million micrometeoroids of 1 g falling on Earth annually [10]. Though, this issue still needs to be analysed thoroughly.

A larger issue would arise if catastrophic failure occurs during the launch as smaller debris would be rejected. If launchers may fail and explode high in atmosphere, a shell of debris will form over time, making any further space exploration mission nearly impossible.

3.2.6 Effect on plants

Another important risk of the method is it's effect on the plants on Earth. Given that sunlight is one of the main needs of plants, the technique can prove to effect them significantly. If humans would not interfere, the biodiversity of plants would decrease significantly after implementation of a sun-blocking technique as many species would not be able to exist with the new sunlight radiation. A solution to this would be to artificially grow these necessary plants, however this would involve techniques that emit lots of greenhouse gasses to produce the energy necessary for the production of this biomass. This would of course be very inefficient as the underlying problem that space mirrors try to solve is still the excessive emission of greenhouse gasses. So in order to prevent this, research should be done to determine the effect of the decrease in sunlight influx on different important plant species (such as fruits, grass, trees etc.). This way, specific techniques can be developed to prevent the extinction of certain plant species after the implementation of the space mirrors technique.

Moreover, a decrease in plant life can have other huge effects on the climate. Plants remove more than 29% of CO_2 emissions [24]. So a decrease in the amount of plants can have serious consequences for the amount of greenhouse gasses in the atmosphere. This would again reduce the net effect of the solar radiation blocking technique, as the underlying problem is only made worse.

3.3 Reversibility

Knowing the possible risks that come with the implementation of space mirrors, it's important to analyse the scenario where we might want to reverse the effects of the implementation. Since effects can only be predicted with a limited degree of certainty, a situation might arise where a space mirror solution is implemented without a confident grasp on all of it's effects. Reversibility is a key aspect in such a situation and is thus an important parameter in the decision to implement a space mirror technique. This section will analyse the possibility of reversing the possible harm caused by the implementation of space mirrors in greater detail.

3.3.1 Lifetime exceeding

Firstly, the expected lifetime of space mirrors could be up to 50 years, depending on what exact type would be used [25]. After the end of this period, most of the debris from the space mirrors will go into heliocentric orbit. A part of the debris will also find their way back to Earth. According to [26], this threat is no greater than the annual threat of natural objects hitting the Earth (see also subsection 3.2.5).

3.3.2 Solutions for reversibility

Space mirrors do thus not pose an unacceptable threat after their expected life time. They could however have harmful effects before this time (examples listed in section 3.2). The question therefore arises if the effects of a space mirror solution can be artificially stopped after implementation in a scenario where this is desired. This subsection will analyse this reversibility for both the cloud and ring concept.

Cloud concept

A possible solution for the cloud concept would be to control the lateral and rotational motion by varying the radiation pressure on each individual flyer [26]. Being able to control the position and rotation of the flyers gives the ability to control the effective sun-blocking area of the cloud as is illustrated in Figure 3.3. In this way, the percentage of reflected sunlight could be adjusted if this is desired. The proposal of [26] does include a way to control the lateral and rotational motion of the flyers, which means that with enough research, this method can definitely be made reversible.

Another option that would completely stop the mirrors from reflecting sunlight for the cloud concept would be to bring them into halo orbits [3] around the L1 axis [26]. This option is however much less feasible and has more drastic engineering consequences as this would require some sort of engine system in order to propel the flyers into this orbit. This would increase the costs of the cloud concept significantly, because of the fact that the system of the flyers becomes more complicated and because of the increased mass of the flyers that have to be launched in this scenario. The process of sending the flyers into a halo orbit would also not be perfect, giving rise to the possibility of flyers falling back to Earth or remaining some form of reflection.

Ring concept

The reversibility of the ring concept is one of it's major drawbacks. There is no clear way to eliminate the effects of the ring after it's implementation on a very short time scale (such as the time it takes to rotate the flyers in the cloud concept). The specific reversibility of the ring concept has not been studied in great detail, however some speculative comments can be made for long-term removal mechanisms.

Space debris removal systems as described in [27] might be a solution according to the proposal of the ring concept in [13]. These space debris removal have however mostly been researched for Low Earth Orbits, whilst the ring concept is not proposed for such orbits but rather for bigger orbits.

[3] A halo orbit is a stable three dimensional orbit around a Lagrange point. They exist in any three body system and can be thought of as resulting from a disturbance of the equilibrium of gravitational pull of both the Sun and Earth.

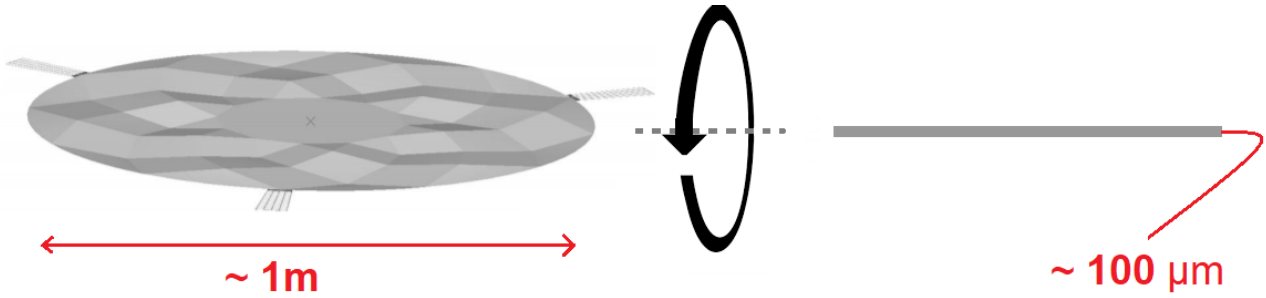


Figure 3.3: Schematic drawing of the differences in effective area that can be achieved through rotation with respect to the Sun (modified from [10])

Moreover, [13] states an interesting observation of the rings of Saturn that form the inspiration for the space mirror ring concept. There are holes in the rings of Saturn that have been created by the moons of Saturn. This leads to the (rather questionable) conclusion that a possible technique for reversibility might be to send a large enough asteroid in the ring orbit in order to fully destabilize it. This is however a very radical and not yet well thought out plan. Debris might fall back to Earth, possible causing harm and the effectiveness of such a method has not yet been confirmed.

Overall, the reversibility of the ring concept is not yet been proven and should therefore still be researched in more detail because a non-reversible technique seems like a bad option for geoengineering at this stage.

3.3.3 Overall reversibility conclusions

Concluding, reversibility is an important requirement for any geoengineering technique as side effects and efficiency can mostly only be predicted with a limited degree of certainty. Because of the high risks of a space mirror solution as discussed in section 3.2 and the high life time as discussed in subsection 3.3.1, it is especially important for the space mirror techniques to be reversible. From the analysis of both cloud and ring concept, it has become apparent that the cloud concept has better prospects to be reversible compared to the ring concept.

Discussion 4

This chapter considers multiple aspects of importance for the assessment of a geoengineering technique. First the feasibility of the methods previously outlined is investigated in section 4.1, then the ethics of the general concept of space mirrors are analysed in section 4.2. Finally, comparisons between the cloud and the ring concept but also with other geoengineering techniques are given in section 4.3.

4.1 Feasibility

The feasibility of the method largely depends on the cost and the readiness of the technology and policy involved. Those aspects differ for the cloud and ring concepts presented in chapter 2, they will both be presented in this section.

4.1.1 Cloud Concept

The cloud concept relies on the availability of new advanced technology in the field of launchers, the lifetime of the flyers, the possibility to reduce greatly the production and launch costs and the ability to mass-produce the flyers in quantities unheard of.

The mass production required for such mission has never been reached before in any field as around 16 trillion flyers will be required, this will probably require the mass production of the autonomous production lines of the spacecrafts. By mass-producing the flyers, the manufacturing cost per kg can be significantly drop compared to current spacecrafts. An example, at a much lower scale, of spacecraft mass-production is given by Starlink who intend to launch 12,000 small satellites in LEO [28]. The cost per satellite is also estimated to be 250,000 US$ (Fiscal Year 2019) for around 260 kg [28, 29]. Giving a cost of 962 $/kg, which is far below the cost of the Iridium spacecrafts of 7,000 $/kg for 100 spacecrafts [10] (which is already around ten times less than for a single spacecraft mission). As a comparison, computers usually cost around 100 $/kg. From this train of thought, it is reasonable to think that the cost of the flyers could reach around 50 $/kg.

Considering the lifetime of the flyers, current high orbit complex spacecrafts can stay in operations for about 20 years [30]. A simple flyer with enough electronic redundancy and derated solar cells against solar radiation should be able to achieve lifetimes of 50 years [10].

All flyers would be designed on Earth to be launched in space. This reduces greatly the complexity of the mission as in-space manufacturing and assembly is not yet a viable option. However, this increases the need for a low-cost launch option.

Low-cost Launch

The use of Electromagnetic launchers has been considered by [10] as a way to cheaply get the flyers in LEO. However, this technology has yet never been used in practice. Three main methods are discussed in literature: the coil gun, the linear accelerator and the railgun concepts [12] but only the latter has been demonstrated to have the potential to accelerate payload to velocities great enough to reach LEO (7.9 km/s). [12] showed multiple major issues considering the current development of EM launchers:

- The market demand is lacking. EM launchers are being considered for small payload that is not fragile (due to the very high accelerations encountered).

- Launch site is a lot more critical than for conventional vertical rockets as little maneuver can be performed during the launch. This means that the EM gun needs to be oriented in a specific direction for launch. Making one facility adapted for multiple application to boost development would require a lot of added complexity.
- The flight body will need to travel at great velocities throughout the atmosphere, putting emphasis on the aerodynamic shape of the capsule and requiring a minimum drag. Those are very strong requirements for the flight body and it will therefore be an expensive part of such launch system. Being able to use it multiple times could reduce the overall cost even more.

Overall, the EM launcher technology needs more investments to compete with the current traditional technology. A comparison can be made with the development of electric cars which were first investigated in the last part of the 19th century [31] but were quickly dominated by the traditional diesel and fuel based current technology. Now, the system of hybrid and electric cars are gaining attraction and taking larger parts of the market [12]. A similar situation could be envisioned considering the EM launchers in the future if enough national investments are present.

Another difficulty resides in the time frame necessary to launch around 20 million tons of payload. Given that the EM launch technology requires special launch sites and would be a new technology, around 20 EM launchers could be assumed to be used on parallel if the technology ever becomes ready enough. The payload per launch would be around 1,000 kg [10], meaning that the launchers would need to operate every five minutes non-stop for 10 years. This is of course also dependent on whether the 800,000 flyers per launch can be manufactured fast enough as a starter (they would need to be manufactured ahead of time and stored).

On the other hand, ion propulsion can be used to reach L1 from LEO in a few months with little amounts of propellant thanks to the large exhaust velocities amounting to several dozens of kilometers per second.

Cost

Overall, nothing stands against the use of this technology apart from the technology readiness of EM launchers, the rest of the technology is known and could be applied anytime if done well ahead (taking more than 10 years to not rely on the constant launch of the flyers). The main feasibility concern of this geoengineering technique concerns the cost as it would amount to about 5 trillion dollars (F.Y. 2006) including development and operations. This cost averaged on the 50 years of lifetime would come to about 100 billion $ per year, which is around 0.2% of the world GDP (F.Y. 2006). This is of course a very high cost but the risks of climate change might one day justify such approach to have more time at hand to save the planet.

4.1.2 Ring Concept

The feasibility of the ring concept is most likely its biggest downside, as it relies on multiple different scientific breakthroughs in the field of spacecraft engineering. The component of the proposal that needs the most scientific breakthroughs is the asteroid mining system [14]. This system needs to mine asteroids for dust particles and either give them the right velocity to get into the right orbit around Earth, or to store them and transport all dust particles in 1 trip back into the feeder orbit. Such a system is not feasible with the current technologies, however some proposals for this system have already been made, relying on future developments. After this engineering problem, there is also the problem of constructing the system that feeds the particles into orbit. Once all these engineering problems have been resolved, it is still unclear if this method is feasible. On the one hand there is the uncertainty about international cooperation to implement this technique, on the other hand there is the uncertainty of the risks.

Asteroid mining system

In [32], a mass driver was proposed that could retrieve material from asteroids near Earth and send them back to Earth. This proposal was made in 1977 and the author believed that such a system could be developed within 10 years. The estimation has turned out to be rather bad, but this does show how such missions might be possible in upcoming years. The problem however is that the process does not only need to be carried out once, but should be done periodically and automatically over a period of roughly 10 years. This gives a lot of engineering problems (such as energy necessity and re-usability). Moreover, the asteroid mining system should be able to transport it's milled asteroid particles to the orbit feeding system in a way to minimize the loss of these particles.

Orbit feeding system

The mechanism for feeding the dust particles into the right orbit to form a stable ring is another challenging engineering problem. A possibility for this problem is the solution as presented in [16], where a launch system on the moon is proposed, combined with a 'catching mechanism' in an elliptic Earth orbit. The launch system of this proposal does however depend on the existence of Electromagnetic launchers as presented in Figure 2.4 and Section 4.1.1. As explained, these Electromagnetic launchers have not yet been implemented because of the lack of research in the field. Enough funding might resolve this issue, but this certainly gives an even higher uncertainty about the feasibility of such a system.

International cooperation

To implement a technique such as the ring concept, there has to be a form of international cooperation to support the execution of the proposal. For any geoengineering project this cooperation can be doubted, however this doubt is even stronger for this specific proposal. This is because of the fact that there will be a lot of local effects. The cooling of the earth is of course stronger in regions where the particle ring directly blocks part of the incoming sunlight. According to the proposal by [13] (see Figure 2.5a), these effects will most likely be higher for regions close to the equator. Such a decrease in incoming sunlight can have very big and direct effects on the agriculture and overall ecosystems in these regions. This will probably cause governments near the equator to be very sceptic about the ring concept, which harms its feasibility. And even if a stage of international agreement on the fact that the ring concept can be used is reached, it is still unclear who should be implementing it.

General uncertainty on feasibility

If all these engineering problems are overcome within the next few decades, then the feasibility of the project is still in doubt. According to [13], the ring should be slowly constructed in phases. These phases should have enough time in between them as to evaluate the impact that the new particles in orbit have. These time scales are of course highly dependable on the urgency of the cooling of the Earth and therefore the risk that will be taken. This does however show that the feasibility of the concept is highly dependent on the amount of risk that one wants to take. If the concept is implemented and it does work, it will do an effective job at cooling the Earth, however if it fails it might also have drastic influences.

4.2 Ethics

The ethical aspect of any geoengineering technique is very important to consider as the technology will have a global effect and more local consequences. It is important that all stakeholders have their say in the discussion and that a consensus is reached concerning the implementation or not of the technology. In case more local effects are expected to occur in some particular regions of the world, the countries concerned might require compensation or arrangements such that the political climate stays sustainable during the complete implementation of the geoengineering technique. All these different aspects will be considered in this section.

4.2.1 Balance Geoengineering and Mitigation

A geoengineering method of any kind is in no way a solution to the climate change problem at stake. The climate crisis arose from the current living style of society, and therefore, the use of geoengineering shall not diverge the focus of solving the problems of greenhouse gas emissions using mitigation and adaptation. The complete goal of such a technique is to save some time for a more adequate reaction to the crisis and avoid an imminent tipping point. This is called moral hazard [21] and is mostly unpredictable, this was already mentioned in subsection 3.2.2.

The cost of a geoengineering technique might also hinder the transition to a more sustainable society relying on green energy and others. This should never become an issue as the time bought by the geoengineering method would then be compensated by the lack of funding available to solve the true issue. This implies using the budget of other domains of society such as military or other 'less' important matters for the time of the implementation and management of the geoengineering technique. This is of particular concern when it comes to space mirrors as their overall cost are a significant part of the world GDP. The question of which domains of society are 'less' important is of course a very difficult one and will have different answers for different groups of people.

4.2.2 Uncertainty and Risks

The main risks and uncertainties of the method of space mirrors were presented in section 3.2. Although those seem to be less undesirable compared to the primary effects of climate change, they need to be investigated further and better understood. However, it is never possible to entirely know the consequences of the method before its implementation and some risks might be found to have been underestimated. In case the side-effects turn out to be more significant then expected, it is necessary to reverse the method by the use of a termination mechanism [33], this is also of a large importance due to the large expected lifetime of such systems (around 50 years). Some ideas for such operation in the case of space mirrors were presented in chapter 3.

In the cloud concept, the reversibility can be done in a quite straightforward manner within a very small time frame, but the ring concept does not have such alternative. This termination mechanism is often a downside of other methods such as SAI as removing particles from the air in a quick time is nearly impossible to do. This is one of the strong points of space mirrors in terms of geoengineering.

However, if reversibility (for any reason) was to be applied after multiple years of application of the technique, the temperature rise due to the additional accumulated carbon in the atmosphere would be very sudden [33]. Certain species, such as mankind itself, might not be able to adapt rapidly enough to survive. The climate crisis is already a huge problem to tackle but this scenario would make the entire situation much worse. This is called the termination problem.

4.2.3 Politics

The implementation of any geoengineering technique is also complicated by the ethics that arise in the politics of such a technique. Questions arise such as: Does support for such a technique have to be unanimous in order to proceed with implementation? If not, what percentage of countries have to agree with it? Which countries have to be considered with this voting?

The problem with a justice basis of a decision on a geoengineering proposal is that all citizens can reasonably claim to be stakeholders. As stated by [34]: "The prospect of controlling the global thermostat is something that all citizens could reasonably claim to have a legitimate stake in". In a 'normal' engineering project, engineers should always take input from all stakeholders, however accounting for over seven billion citizens is an impossible task.

This problem thus requires new governance procedures according [21], which it states is an "enormous task". The exact form of such a system has not yet been made concrete. However, as climate change effects become more apparent it is expected that the needs for such systems will drive its development. It should however be noted that a hasty forming of such a system will not improve its working, so starting early with its development is definitely advised.

Moreover, because of the local effects that the space mirror proposals are bound to have, such a concept might also be used as a means of strategic warfare between countries according to [21]. If further research in both space mirror solutions show significant negative effects towards one region of countries compared to some other region, this solution might be pushed by the countries benefiting from it without regard to the actual environmental impact. It is therefore also necessary to keep caution when analysing geoengineering techniques for the possible framing that can be done by countries that benefit from a certain type of geoengineering.

4.2.4 Financing

Another interesting dilemma that arises with the analysis of the implementation of a space mirror (or any geoengineering) solution is the problem of financing it. The question 'Who will pay for the implementation of the technique?' is central here. An option is to distribute the costs according to the GDP of each country. This does however not account for the fact that the richer countries have played bigger parts in the cause of the problem: greenhouse gas emissions.

Since the implementation of a space mirror technique will cause local effects, certain countries will suffer more from its implementation than others. [21] argues that the side effects of geoengineering techniques can hardly be predicted. A compensation mechanism should thus focus on planning for helping certain populations with water, house rebuilding and moving of people.

Lastly, it should be noted that an organisation implementing a geoengineering technique such as space mirrors should never be operated privately [21]. If such an organisation is operated privately, it might benefit those who can pay the most instead of those with the highest needs, which is definitely not a moral cause of action.

4.2.5 Future generation

The ethical questions arising with the implementation of geoengineering do not only cross the boundaries of this generation, they also cross the generational boundaries. An important question to ask before the implementation of any geoengineering method is: 'What burdens can be left for future generations and what risks are morally acceptable to take regarding future generations?'. This is an ethically impossible question to answer, however some comments can be made. An important aspect of a technology regarding this question is its reversibility. It seems morally unjustified to implement a technology and thus knowingly taking some risks, while future generations can not reverse it's possibly negative consequences. With regard to space mirrors, the reversibility of the ring and cloud concept have been analysed in section 3.3.

4.2.6 Conclusion on ethics

Concluding, this section has given some insight into the complex moral, political and generational questions that arise when analysing the ethics of the implementation of a space mirror geoengineering technique. Giving a concise conclusion for the ethical question if a geoengineering solution should be implemented at this stage is thus very difficult. [21] (written in 2013) concludes that in the current stage of the world, any geoengineering solution can not yet be ethically justified. It does however state that this conclusions is already way harder to make compared to about 20 years ago.

4.3 Comparisons

One of the goals of this report was to locate the idea of space mirrors in the field of geoengineering and to assess which of the cloud or ring concept would be preferred if one had to be chosen for implementation. This section aims at comparing the two concept with each other but also to reflect on its relevance with respect to other geoengineering techniques such as Stratospheric Aerosol Injection and the Carbon Capture technologies.

4.3.1 Comparing the Cloud and Ring concepts

In comparing the cloud concept and the ring concept, one of the most notable differences is the seasonal dependence of insulation of the ring concept. As discussed in the chapter 2, the insulation drops significantly during Spring and Autumn compared to other seasons. This will change the seasons and might highly affect ecosystems and people. This change in insulation throughout the year needs to be investigated further to quantify its effects on the economy and ecosystems of the concerned regions. At this moment, those exact effects have not yet been quantified enough to evaluate the possible compensation necessary for the regions affected or to fully evaluate its negativeness. But this drawback is not present when considering the cloud concept. Apart from the seasonal effect of the ring concept, the risks and benefits of both ideas are mostly similar.

Another difference aspect of both concepts is their reversibility. Only the cloud concept is really reversible in some sense. As explained in section 3.3, it could be done by placing them into Halo orbit or by rotating them such that the percentage of reflected sunlight is largely negligible. The ring concept is lacking any real reversibility method as it comes back to the field of de-orbiting space debris which is still an on-going issue. Another way considers the use of a large mass by asteroid capture to remove agglomerate the particles of the rings, however this method still belongs to science fiction. Overall, if there was need to quickly stop the method of space mirrors, the cloud concept is the only one that could be reasonably stopped.

The feasibility of the cloud concept resides in the development of EM launchers to LEO being researched at this moment and the capacity to mass produce small spacecrafts. The latter can certainly be reached easily as society is mostly based on mass-consumption and hence production. The former will take more time, as was assessed in subsubsection 4.1.1. The ring concept is based on the capture and mining of an asteroid, which can be vastly considered as science-fiction at this moment.

The expected cost of the ring concept is also about five times larger than the cloud concept estimated cost. Those economics consideration need to be researched further upon but it seems like the cloud concept would again be more realistic on an economic basis.

Altogether, the ring concept is surrounded with more doubts on both the risks, costs and feasibility than the cloud concept. This makes the cloud concept currently the preferential option but this could change overtime depending on the state of the art in the future and the results of further research on both concepts.

4.3.2 Comparing space mirrors and SAI

The implementation of SAI completely relies on technology that is already known and is therefore very feasible. On the other hand, the cloud concept of space mirrors still depends on the development of future technology such as the EM launchers. If a technique was to be implemented within a few months, SAI would be ready while space mirrors require much more time for implementation.

The risks associated with the cloud concept are significantly less significant than those of SAI. The two techniques share most of the solar reduction related side effects, but importantly the space mirror cloud concept does not suffer from the sulphur related side effects. These could affect people's health and ecosystems. In addition, SAI could also delay ozone layer recovery. Lastly, SAI would also have a major impact on terrestrial optical astronomy, by putting permanent pollution above telescopes [35]. If safety is the first concern, space mirrors might be the first choice.

SAI is far cheaper than space mirrors: it costs only several billions dollars a year [35]. Space mirrors will cost hundreds of billions of dollars per year. Using SAI instead of space mirrors, this money could be allocated to solve other global issues or to better invest in the transition to green energy such that geoengineering needs to be used for the smallest amount of time possible. Although, 0.1% of world GDP annually is a modest price to pay to mitigate climate change and avoid side effects. The question thus becomes if the relative safety that comes with space mirrors is worth the extra costs that they come with compared to SAI.

Altogether, SAI is cheaper and easier to implement. However, space mirrors could avoid some of the side effects of SAI. These side effects also have a high cost. Currently, SAI is the more logical option to implement, but this could change with new technological developments. Therefore, SAI and space mirrors should both be investigated further.

4.3.3 Comparison of space mirrors with Carbon Dioxide Removal methods

Another well-established category of geoengineering solutions to combat the heating of the planet are Carbon Dioxide Removal (CDR) methods. These solutions aim to solve the problem of greenhouse gasses at the root by trying to remove CO_2 from the atmosphere. There is a wide range of possible CDR techniques, however for the purpose of this comparison, some generalizations about CDR techniques will be made to compare space mirrors to CDR techniques in general.

One major difference between CDR techniques and space mirrors (or any Solar Radiation Management technique) is that it solves the problem at it's roots. CDR techniques are designed to directly capture carbon dioxide out of the system, which partly solves the problem of excessive greenhouse gasses. Space mirrors on the other hand can only aim to reduce the temperature on Earth to give mankind time to try and solve the main problem of greenhouse gasses in the atmosphere.

A big downside to CDR techniques in general is that their effects will most likely only be felt after more than a decade from their implementation [36]. This means that if a geoengineering solution becomes an urgent need to solve the heating of the Earth, a plan that only contains CDR techniques will not suffice to perform this task. Combining CDR techniques with space mirrors (or any other form of SRM) might be a better fit as space mirrors have the big benefit of showing high cooling effects on relatively low time scales.

Moreover, most individual CDR methods do not yet have the capacity to negate enough CO_2 in order to actually reduce the amount of CO_2 in the air given the amount of global emissions [36]. So this means that multiple different CDR methods must be used simultaneously in order to reduce CO_2 levels in the atmosphere. On a long-term scale, this is definitely a feasible solution, however for a short-term cooling solution space mirrors seem more fitting.

Concluding, CDR methods are definitely a great option to use together with some form of Solar Radiation Management such as space mirrors. This is because of the fact that the SRM methods can provide the short-term temperature decreases necessary, while CDR methods might serve to be a long-term solution to the excessive greenhouse gasses in the atmosphere combined with less emissions.

5 Conclusion

The purpose of this report was to analyse the geoengineering technique of space mirrors and to determine what role this technique should play within the quest against climate change. From the discussions presented, it is clear that the technique of space mirrors is only aimed at last resort cases. In case it is known that the tipping point of climate is about to be reached and that only a few dozens of years are still available to counter the tendency, the cost of the technique can then be justified to save the planet and the human civilisation.

The implementation of space mirrors is still far away though, and will require many technological advances, such as electromagnetic launchers or an asteroid mining system depending on the concept at hand. The cloud concept is likely somewhat closer to implementation than the ring concept. Another main issue with the use of this geoengineering technique is the cost which can reach trillions for both the cloud and the ring concepts, amounting to some percentage of the current world GPD (0.2% for the cloud concept and 3.1% for the ring concept annually).

One of the main benefits of space mirrors is that they do not threaten people's health and ecosystems on Earth directly. This is a major advantage in comparison to techniques such as Stratospheric Aerosol Injection. The technique also does not form any danger for already orbiting satellites as both the ring and cloud concepts have a negligible amount of particles that could fall back on Earth compared to already existing space debris and the millions of micrometeorites falling every year on Earth.

However, like other geoengineering options, the hydrological cycle would be affected and other risks are present such as the local effects and the possible response of world leaders to those. Additionally, there is a small chance of excessive reflection due to a bad design, leading to global cooling and the biodiversity of plants will be at risk. Although the effects of such possible global cooling are less important than the ones of climate change as predicted at the moment. Overall, more research is required to better understand the effects of space mirrors on the climate and to assess the potential risks of the method. Some reversibility techniques are also possible such as placing the flyers of the cloud concept in a Halo orbit or to rotate them such that they do not deflect anymore sunlight but that is only applicable to the cloud concept and the ring concept is lacking any realistic reversibility technique.

Altogether, space mirrors are an expensive geoengineering technique to be used only as a last resort. It should also be used in parallel to other techniques such as carbon capture as a space sunshade would only delay the effects of climate change and the necessary changes in society (green energy, necessary policies, etc.) will still be required to have a sustainable mankind living in harmony with its planet. If space mirrors had to be applied and the necessary technology was available, the cloud concept would be preferred due to the more reasonable techniques employed and the lower expected cost. Though, other concepts might be considered and more research is required in general to develop the methods further to make them both feasible and safe.

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