

Annotated bibliography on space-based Geoengineering

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1. Geoengineering overview papers

- 1.1. Burns, L., Keith, D., Irvine, P., & Horton, J. (2019) Belfer Technology Factsheet Series: Solar Geoengineering. *Harvard Kennedy School Belfer Center for Science and International Affairs and Harvard John A. Paulson School of Engineering and Applied Sciences Center for Research on Computation and Society*.
A compact recent summary for policymakers written in collaboration with Ash Carter's program on "technology for public purpose".
- 1.2. Parson, E. (2017) Opinion: Climate policymakers and assessments must get serious about climate engineering. *PNAS*. 114 (35), 9227-30.
A compact opinion piece in PNAS that provides a good recent overview of the policy and politics of Geoengineering
- 1.3. MacMartin, D., Kravitz, B., Long, J., & Rasch, P. (2016) Geoengineering with stratospheric aerosols: What do we not know after a decade of research? *Earth's Future*. 4 (11), 543-8.
An overview of unknowns for stratospheric aerosols, the best known method of solar geoengineering.
- 1.4. Irvine, J., Kravitz, B., Lawrence, M., & Muri, H. (2016) An overview of the Earth system science of solar geoengineering. *WIREs*. 7 (6), 815-33.
An overview of the science focused primarily on model results.
- 1.5. Keith, D. (2000) Geoengineering the Climate: History and Prospect, *Annual Reviews of Energy and the Environment*. 25, 245-84.
An early review with a brief treatment of space-based approaches.

2. Selected formal reports that address geoengineering

- 2.1. National Research Council. (2015) *Climate Intervention: Reflecting Sunlight to Cool Earth*. Washington, DC: The National Academies Press.
- 2.2. The Royal Society. (2009) *Geoengineering the climate: science, governance and uncertainty*.
- 2.3. Institute of Medicine, National Academy of Sciences, and National Academy of Engineering. (1992) *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base*. Washington, DC: The National Academies Press.

3. General Space geoengineering

- 3.1. McInnes, C., Bewick, R., & Sanchez, J.P. (2014) Space-Based Geoengineering Solutions. In R.E. Hester and R.M. Harrison (Ed.), *Geoengineering of the Climate System* (pp. 186–211). Cambridge, UK: The Royal Society of Chemistry.
This is a book chapter and covers a lot of the same material as McInnes 2009 (article 3.4 on this list) but it does the first order calculations for dust clouds and some globally resolved energy balance climate modeling for an occulting disk.
- 3.2. Dicaire, I., Summerer, L. (2013) Climate Engineering: Which Role for Space? *64th International Astronautical Congress. Beijing, China: International Astronautical Federation*.
An overview article that talks about the role of space technologies in geoengineering, this includes: how existing space tech such as lidar/spectrometers can be used for monitoring biomass, reflectivity, chemical composition and ‘visionary’ involvement (ie solar shield). For each technology (sunshade, aerosols, cloud modification, reflective mirrors--mostly discussing earth surface solutions) a summary is given about: how it works, main hurdles, costs in some cases.
- 3.3. Kosugi T. (2010) Role of sunshades in space as a climate control option. *Acta Astronaut.* 67 (1), 241– 53.
Kosugi uses an integrated assessment model (DICE-2007) to examine the optimal shade size and timing of deployment from an economic perspective. Kosugi’s rudimentary model finds that a sunshade would allow for a 15% increase in global CO2 emission in the first half of the 21st century and reduce climate control costs by \$240 billion (2005 USD).
- 3.4. McInnes, C. (2009) Space-based geoengineering: challenges and requirements. *Proceeding of the Institute of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science.* 224 (3), 571–80.
McInnes gives a general overview of what geoengineering is followed by summary of terrestrial and space-based schemes proposed thus far. He does a few simple calculations including: (1) a ‘zero-dimensional model’ of energy balance to estimate the scale of required geoengineering and (2) a first order calculation of occulting disc orbit and size/mass. McInnes also discusses the challenges of fabrication and need for in situ resources.
- 3.5. McInnes, C. R. (2006) Planetary macro-engineering using orbiting solar reflectors. In V. Badescu, R.B. Cathcart, R.D. Schuiling (Ed.), *Macro-engineering: a challenge for the future* (pp. 215–250). Berlin: Springer.
This chapter gives an overview of many of Colin McInnes’ papers (active cooling and heating of the earth, modifying the earth’s orbit) and discusses the scale of these engineering challenges. McInnes also covers a simple energy balance model of both the cooling and heating cases.
- 3.6. Teller, E., Wood, L., & Hyde R. (1997) Global Warming and Ice Ages: I. Prospects for Physics Based Modulation of Global Change. UCRL-JC-128157. Livermore, CA: Lawrence Livermore Natl. Lab.
A idiosyncratic yet systematic overview of the physics of solar geoengineering including space-based systems

4. Proposals (See table for descriptions and parameters at the end of this document)

- 4.1. Sanchez, J.P., & McInnes, C.R. (2015) Optimal Sunshade Configurations for Space-Based Geoengineering near the Sun-Earth L1 Point, *PLoS One*, 10 (8)
- 4.2. Bewick, R., Lucking, C., Colombo, C., Sanchez, J.P., & McInnes, C.R. (2013) Heliotropic dust rings for Earth climate engineering. *Advances in Space Research*. 51 (7), 1132-1144
- 4.3. Bewick, R., Sanchez, J.P., & McInnes, C.R. (2012) The feasibility of using an L1 positioned dust cloud as a method of space-based geoengineering. *Advances in Space Research*. 49 (7), 1212–28.
- 4.4. Struck, C. (2007) The Feasibility of Shading the Greenhouse with Dust Clouds at the Stable Lunar Lagrange Points. *Journal of the British Interplanetary Society*, 60 (1), 82-89.
- 4.5. Angel, R. (2006) Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). *Proceedings of the National Academy of Sciences*, 103 (46), 17184-17189.
- 4.6. Pearson, J., Oldson, J., & Levin, E. (2006) Earth rings for planetary environment control. *Acta Astronautica*. 58 (1), 44-57.
- 4.7. McInnes, C.R. (2002) Minimum mass solar shield for terrestrial climate control. *Journal of the British Interplanetary Society*, 55, 307-311.
- 4.8. Hudson, H. S. (1991) A Space Parasol as a Countermeasure Against the Greenhouse Effect. *Journal of the British Interplanetary Society*, 44, 139-141.
- 4.9. Mautner, M. (1991) A Space-Based Solar Screen Against Climate Warming. *Journal of the British Interplanetary Society*, 44, 135-138.
- 4.10. Mautner, M., & Parks, K. (1990) Space-based control of the climate. *Engineering, construction, and operations in space II*, 1159-1169.
- 4.11. Early JT. (1989) Space-based solar shield to offset greenhouse effect. *Journal of the British Interplanetary Society*, 42, 567–69.
- 4.12. Seifritz W. (1989) Mirrors to halt global warming? *Nature* 340, 603.

5. Space items related to geoengineering

General development of space resources

- 5.1. Fu, B., Sperber, E., & Eke, F. (2016) Solar sail technology—A state of the art review, *Progress in Aerospace Science*. 86, 1-19.
Fu *et al* provide a review of solar sail technology to date including radiation pressure force modeling and attitude and orbital control. There are a few passing mentions about sails at L1, but this article does not mention how solar sails could play a role in space-based solar

geoengineering. However, it does provide an introduction to thinking about transport and stability of a space-based solar geoengineering project.

- 5.2. Hemsell, M. (2006) Space power as a response to global catastrophes. *Acta Astronautica*. 59, 524-530.

Hemsell gives an overview of how harvesting solar power in space could play into future energy portfolios, including as a power source for carbon dioxide removal. Development of these solar power satellites (SPS), would mean advance development in extraterrestrial mining. Hemsell estimates that the mass of scale of a constellation of SPS would be comparable to the 1824 km radius, 410 Mton shield presented in McInnes (2002).

Asteroids/Resources/Orbits

- 5.3. Vdovin, G., Sarro, P., Soloviev, O., Loktev, M., & Angel, R. (2015) Structured film for compensation of anthropogenic radiative forcing. *Optics Letters*. 40 (8). 1702-4.
This paper explores the types of films that could be used for a solar shade. The authors assume that the shade would be near L1 and be 1 g/m² or less. They emphasize that the film must have high longevity, low density, high on-axis scattering (70-90%), low reflectivity over solar spectrum, foldability, and robustness. Their candidate is perforated silicon nitride film where the perforations serve as “stops” for tears. Currently the films can only reach maximum sizes of cm and do not satisfy the back-reflection requirements.

- 5.4. Bewick, R., Sanchez, J.P., & McInnes, C.R. (2013) Usage of Asteroid Resources for Space-Based Geoengineering, In V. Badescu (ed.) *Asteroids* (pp581-603). Berlin: Springer.

Bewick *et al* summarize the various space-based solar geoengineering method which employ asteroid resources including: an unstable dust cloud at L1 (capture and position asteroid near L1, mine asteroid and eject dust from it, ejected dust used for shielding and stabilizing the asteroid), a gravitationally anchored dust cloud (using larger asteroid), and an earth ring (asteroid captured in an equatorial generator orbit, dust extracted from asteroid is ejected into feeder orbit which evolves into dust ring). The authors give an estimate of the energy required to obtain the asteroid sources for each of these methods and conclude that material for a gravitationally anchored dust cloud or an earth-moon L4/L5 cloud could not be supplied entirely with asteroid material that is more accessible than the surface of the Moon.

- 5.5. McKay, R., Macdonald, M., Biggs, J., & McInnes, C., (2011) Survey of Highly Non-Keplerian Orbits with Low-Thrust Propulsion. *Journal of guidance, control, and dynamics*. 34 (3), 645-666.

McKay *et al* explore propelled orbits where the time average of the acceleration is of at least equal magnitude, if not greater than, that of the sum of the gravitational and centripetal accelerations experience by the object. These orbits can be achieved using low-thrust spacecraft. The authors discuss the mechanics of both 2 and 3 body systems including halo orbits about displaced Lagrange point and highlight that these orbit could be used for telecommunications (polar, interplanetary, lunar), polar observations of the earth, observations of Saturn’s rings, asteroid investigations, and space-based geoengineering.

- 5.6. Biggs, J.D., & McInnes, C.R., (2010) Passive Orbit Control for Space-Based Geo-Engineering *Journal of Guidance, Control, and Dynamics*, 33 (3), 1017-1020.
The authors suggest using a passively stabilized solar sail to help stabilize a reflector at L1. This would be accomplished by adjusting beta, the ratio of solar radiation pressure acceleration to solar gravitational acceleration, through the attitude and pitch of the shield. One method, which the authors call a 'solar balloon', would be a structure that expands due to temperature as it gets closer to the sun. This increases surface area increases beta accelerates the sail away from sun. Another method could use a variable reflectance material or heat sensitive actuators to adjust the structure. The authors note that the purely passive case it is only stable with injection error around 20,000 km in the ecliptic plane.
- 5.7. McInnes, C.R., McDonald, A.J.C., Simmons, J.F.L., & MacDonald, E.W. (1994) Solar sail parking in restricted threebody systems. *Journal of Guidance, Control, and Dynamics*. 17 (2), 399–406. An examination of orbit for transporting and parking a solar sail in either the earth-sun or earth-moon system while accounting for solar radiation pressure. Generally, the solutions are unstable but a simple closed-looped control system that can ensure stability is discussed. Station keeping is achieved by using trims on the sail attitude. This analysis is for general space-based endeavors and not specific to geoengineering, but Colin McInnes is the first author and he has clearly thought about space-based solar geoengineering a lot.

Other similar systems

- 5.8. Salazar, F.J.T., & Winter, O.C. (2019) Sun-synchronous solar reflector orbits designed to warm Mars. *Astrophysics and Space Science*. 364 (9) 1-10.
This paper discusses the orbital dynamics of solar reflectors to terraform Mars.
- 5.9. Schmitz, B., Farley, K.A., Goderis, S., Heck, P.R., Bergstrom, S.M., ... & Terfelt, F. (2019) An extraterrestrial trigger for the mid-Ordovician ice age: Dust from the breakup of the L-chondrite parent body. *Science Advances*. 5 (9).
This paper argues that ice age conditions in mid-Ordovician (466 Ma ago) were triggered by meteorite breakup that made inner solar system dusty and fertilized oceans. Most of the paper is about paleoclimate, but the authors have one paragraph referencing applications to geoengineering and the idea of gravitationally anchoring a dust cloudy at L1.
- 5.10. Salazar, F.J.T., McInnes, C.R., & Winter, O.C. (2016) Intervening in Earth's climate system through space-based solar reflectors. *Advances in Space Research*. 58, 17-29.
In this paper the authors look at the inverse situation, increasing insolation is required to manage a fast cooling event on earth. They proposed to put solar reflectors on a polar orbit normal to ecliptic plane of Earth to increase insolation by 0.5%. They include an orbital dynamics analysis of a non-Keplerian orbit for this situation and include the J2 perturbation (oblateness of the earth) to increase accuracy of the model.

6. Even crazier ideas (changing the earth's orbit)

- 6.1. McInnes, C. R. (2002) Astronomical Engineering Revisited: Planetary Orbit Modification Using Solar Radiation Pressure. *Astrophysics and Space Science*. 282 (4), 765-772.

The authors discuss modifying the earth's orbit using solar sails as opposed to using grazing flybys of small solar system bodies.

- 6.2. Korycansky, D., Laughlin, G., & Adams, F. (2001) Astronomical engineering: a strategy for modifying planetary orbits. *Astrophysics and Space Science*. 275, 349-366.

The authors present a method of modifying the earth's orbit outward using a Kuiper Belt object or asteroid and a gravitational assist from Jupiter. This method would require one encounter every 6000 years.

Paper	Type	Location	Mass (tonne)	Area (km ²)	Material	Notes and concerns
Early (1989)	Reflecting or refracting disc	Solar L1	1.0E+08	3.1E+06	Lunar	· Almost constant shading across earth except arctic regions
Seifritz (1989)	Reflecting disc	Solar L1	4.5E+07	4.5E+06	Earth	· This is a correspondence letter, so it's very short, published a few months before Early paper · Energy required estimate: 30 1 GW nuclear power station running for 20 years · Active stabilization
Mautner (1990)	Array of screens	Solar L1 or sunwards of L1	3.4E+07	1.0E+06	Earth, Lunar, or Asteroid	· Discusses different material density max for locations out to 0.5au · Mentions selectively filtering some UV wavelengths · Concerns that screen could be used for weather control
Hudson (1991)	Array of screens	Low earth orbit	6.4E+08	1.3E+07	Earth, Lunar, or Asteroid	· Geosynchronous options is very low efficiency · Greatly affect solar astronomy
		Geosynchronous	4.3E+10	8.8E+08		
		Solar L1	1.2E+08	1.5E+06		
Mautner (1991)	Array of screens	Equatorial ring (1.01-3 earth radii)	3.0E+08	Width >300 km	Lunar or asteroid	· Proposed a thin film 'belt' but notes it cannot be continuous due to tidal forces · Instead suggest built as a series of island supported by mesh · Briefly discusses dust ring and shield · Projected costs: \$100 billion - \$1 trillion
McInnes (2002)	Array reflecting disc	Solar L1	4.2E+08	1.0E+07	Asteroid	· Goes through general physics calculation for size and location and tradeoffs between mass, area, and exact location near L1 · Raises issue of sun flickering and orbital debris hazard

Paper	Type	Location	Mass (tonne)	Area (km ²)	Material	Notes and concerns
McInnes (2006)	Array reflecting disc	Solar L1	2.6E+08	6.6E+06		<ul style="list-style-type: none"> · In addition to calculations for a reflecting or absorbing disc at L1, chapter gives overview of active cooling/heating of the earth and modifying the earth's orbit · Discusses scale of these engineering challenges · Uses an energy balance model
	Array absorbing disc	Solar L1	4.9E+07			
Angel (2006)	Array of 1m spacecraft	Solar L1	2.0E+07	4.7E+06	Earth	<ul style="list-style-type: none"> · Spacecraft over dust for active stabilization · Delivered using ion propulsion · 25-year estimate · Projected costs: \$600 billion
Pearson (2006)	Dust ring	Equatorial ring (1.3-1.6 earth radii)	2.3E+09	5.0E+06 to 3.7E+07	Asteroid	<ul style="list-style-type: none"> · Discusses shepherding asteroids · 6 different ring altitudes with constant mass so opacity changes · Mostly would shade tropics · Discusses development scenario · Considers a 1D atmospheric model · Projected cost dust ring: \$6-200 trillion · Projected cost satellites: \$125-500 billion · Concerns: small particle fall out disrupts LEO satellites, bright nights, amplified seasonal effects
	Tethered spacecraft with 1 km ² parasols	Equatorial ring (1.2-1.5 earth radii)	5.0E+06			
Struck (2007)	Dust cloud	Lunar L4/5	2.1E+11	3.4E+09	Comet, lunar	<ul style="list-style-type: none"> · Radiation pressure · 100-year estimate · Concerns: difficult to remove, bright nights and ecological ramifications

Paper	Type	Location	Mass (tonne)	Area (km ²)	Material	Notes and concerns
Bewick (2012)	Dust cloud	Solar L1	7.6E+07	7.8E+05 to 6.2E+08	Asteroid	<ul style="list-style-type: none"> · Has quick comparison of all techniques to date · Looks at lifetime as function of grain size · Has comparison of energy required to implement various proposals · Uses solar radiation model for calculating attenuation · Examines methods of generating the dust including: sublimation from asteroids, mass driver lander, and spin fragmentation · Construction would take 30 years
Bewick (2013)	Dust ring	Equatorial ring	1.0E+09		Asteroid	<ul style="list-style-type: none"> · Use similar approach as Pearson (2006) · Explores different orbits and particle distribution that are more stable · Would focus on low tropical regions · Concerns: increased seasonal variations, affect spacecraft and communication from geostationary satellites, difficult to remove
Sanchez (2015)	Array of 2 disks with out-of-plane displacements	Solar L1	1.0E+08	6.5E+06		<ul style="list-style-type: none"> · Globally resolved energy balance model has 3 vertical layers (ocean, surface, atmosphere) · Looks for optimal shade config that returns earth to control