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Intervening in Earth's climate system through space-based solar reflectors

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Abstract

Several space-based climate engineering methods, including shading the Earth with a particle ring for active cooling, or the use of orbital reflectors to increase the total insolation of Mars for climate warming have been considered to modify planetary climates in a controller manner. In this study, solar reflectors on polar orbits are proposed to intervene in the Earth's climate system, involving near circular polar orbits normal to the ecliptic plane of the Earth. Similarly, a family of displaced polar orbits (non-Keplerian orbits) are also characterized to mitigate future natural climate variability, producing a modest global temperature increase, again to compensate for possible future cooling. These include deposition of aerosols in the stratosphere from large volcanic events. The two-body problem is considered, taking into account the effects of solar radiation pressure and the Earth's J_2 oblateness perturbation.

Keywords: Space reflectors; Polar orbits; Non-Keplerian orbits; Earth's climate system; J_2 perturbation; Two-body problem

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1. Introduction

Simple climate models help to explain the natural variability of the Earth's climate system (McGuffie and Henderson-Sellers, 2005). These models show that Earth's climate can switch from a stable warm state to a cool state and is sensitive to relative small changes in solar insolation (Berglund and Gentz, 2001; Emanuel, 2002; Allen et al., 2006). The periodicity of ice ages (Milankovitch cycles) (Muller and MacDonald, 1997) can be explained by these processes. These cycles are due to a combination between oscillations in the elements of the Earth's orbit about the Sun, and periodic changes to the orientation of the Earth's spin axis, which change the relative flux of energy received by the Earth at polar and equatorial latitudes. Although the total change in insolation due to Milankovitch cycles is less than 1%, the distribution of heat input as a function of latitude seems to be the main effect (e.g. insolation at high latitudes directly effects the growth and retreat of ice sheets). Similarly, while human-driven climate warming is of contemporary concern, volcanic aerosols reflect sunlight to space and thus reduce solar heating of the Earth, therefore large volcanic-driven forcing can have a significant short-term cooling effect (Angell, 1988; Angell and Korshover, 1984; Zuev et al., 2015), such as Tambora in 1815 (Hansen et al., 1992) or catastrophic super-volcano events, e.g. Toba mega-eruption approx. 71,000 years ago (Zielinski et al., 1996). However, if a period similar to the 'little ice age' (1645–1715) recurred (Le Roy Ladurie, 1971; Free and Robock, 1999), or indeed future large volcanic events occurred, then there could be significant economic consequences for energy demand and agriculture (i.e. energy prices and economic stability). Therefore, it is

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interesting to consider active strategies to avoid such short-term climate change.

Space-based geo-engineering proposals aim to intervene in the climate system by deliberately modifying the Earth's energy balance to reduce or increase the global mean temperature in a controlled manner, with presumed beneficial effect (McInnes, 2010). For example, space-based solar shields have been proposed by various authors to decrease the total solar insolation. Hudson (1991) proposed the deployment of a 10^{11} kg 'space parasol' at the L_1 Langrangian point of the Earth–Sun system to intercept some desired fraction of the solar radiant energy. Similarly, McInnes (2002) proposed the use of a 4×10^{11} kg metallic reflector located sunward of the Sun–Earth interior Lagrange point to offset increases in mean global surface temperature. Angel (2006) also considered cooling the Earth with a cloud of small spacecraft orbited near the inner Lagrange point. In Earth-orbit-based systems, Pearson et al. (2006) proposed an artificial planetary ring about the Earth, composed of passive scattering particles, delivered from the Earth, Moon, or asteroids, and attitude-controlled spacecraft with parasols. However, since thin film devices require terrestrial fabrication and launch at extremely high cost, it is possible that much simpler partly reflecting disks could be extracted from captured near Earth asteroids (McInnes, 2006; Sanchez and McInnes, 2011). Recently, Bewick et al. (2012, 2013) proposed a scheme for dust cloud and heliotropic rings to reduce the manufacturing requirement for space-based geo-engineering at the Earth–Sun L_1 Lagrangian point and medium Earth orbits, respectively. The use of mass drivers to eject material from the asteroid surface, in such a way that the asteroid would be stabilized near L_1, would still be more efficient than lifting material from the surface of the Earth.

In the last forty years, similar geo-engineering schemes have been the subject of numerous studies for a possible futuristic use of orbiting solar reflectors for illumination-from-space applications, e.g. providing extra hours of illumination for energy supplies or terraforming schemes (engineering an Earth-like climate) (Glaser, 1968; Ehricke, 1979; Oberg, 1981; Canady and Allen, 1982; Fogg, 1995). However, as early as 1929, Oberth (1972) had already proposed the use of 'space mirrors' for solar power generation on Earth. The main advantage is the vast energy leverage delivered by the reflectors which is obtained in a relatively short time (Maunter and Parks, 1990). Modest-sized reflectors, of about 20–25 m in diameter, have already flown in space, such as the Russian Znamya space mirror experiment (Leary, 1993). Although the first space mirror experiment (Znamya 2) was a successful, the spot brightness achievable with reflectors of this size is a tiny fraction of the mid-day Sun. For example, McInnes (2002) showed that the required reflector area to increase the total insolation of Mars by 30%, as part of a large-scale terraforming effort, is of order 10^{13} m^2 (and mass of order 10^{10} kg). Similarly, Bewick et al. (2011) proposed the use of a set of 300 Sun-pointing orbiting reflectors with a total system mass of 370 tonnes, to provide sufficient illumination onto the lunar surface to enable the survivability of missions in the long periods of the lunar night. In this manner, large-scale geo-engineering appears to be an interesting tool to explore the possibility of climate heating in order to manage fast cooling events that have occurred in the distant past.

The work presented in this paper aims to investigate the feasibility of using orbiting reflectors on polar orbits in order to explore the possibility of an increase of the total planetary insolation of 0.5% (equivalent to increasing the mean global temperature by 0.5 K) to mitigate against possible large scale climate cooling (Teller et al., 2004). As suggested in McInnes (2010), two candidate orbits for solar reflectors will be evaluated: a Sun-synchronous frozen polar orbit normal to the ecliptic plane of Earth and displaced, non-Keplerian circular orbits. In principle, reflector orbits normal to the Sun-line are more efficient than orbits in the ecliptic plane. This fixed orientation provides additional solar energy transferred to the surface of the Earth. However, reflectors deployed directly in Keplerian orbits about the Earth are strongly perturbed by solar radiation pressure. In this case, displaced circular orbits are an interesting alternative to manage the momentum accumulated by the reflectors. They are essentially circular, near polar orbits but, due to the effect of solar radiation pressure, the orbits are displaced behind Earth along the anti-Sun line (McInnes and Simmons, 1992). In this light, the two-body problem is considered for polar and displaced orbits, including solar radiation pressure (SRP) and the effect of the Earth's oblateness, the J_2 effect. It will be shown that SRP and solar reflector orientation has a significant effect on the orbital evolution. Additionally, the J_2 term will be considered to obtain analytical expressions for the required pitch angle and characteristic acceleration of non-Keplerian equilibrium solutions in a rotating frame of reference. The linear stability of the orbit families will be also investigated. Finally, using the reflector mean distance from the Earth, the area-to-mass ratio and the angle of incidence, the required total reflector area for a 0.5% increase in total insolation will be found.

The remainder of the paper is organized as follows. Section 2 describes a zero-dimensional energy balance model (EBM) and the basic concept for illumination from space. Section 3 describes the necessary conditions to achieve Sun-synchronous frozen orbits considering SRP and the J_2 effect, and numerical experiments for different values of reflector orientation and characteristic acceleration. Section 4 determines the existence and stability of a family of displaced circular orbits when viewed from an internal frame of reference. Section 5 discusses the mass required to fabricate the solar reflector utilizing the polar orbits found in the previous sections. Finally, the conclusions together with the discussion are drawn in Section 6.