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Solar Power Satellite system in formation on a common geostationary orbit

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Abstract. The diurnal day-night cycle severely limits the Terrestrial solar power. To overcome this limitation, a Solar Power Satellite (SPS) system, consisting of a sunlight reflector and a microwave energy generator-transmitter in formation, is presented in this work. The microwave transmitting satellite (MTS) is placed on a common geostationary orbit (GEO) in the Earth's equatorial plane, and the sunlight reflector uses the solar radiation pressure to achieve quasi-periodic orbits about the MTS, so that the sunlight is always redirected to the MTS, which converts the solar energy in electromagnetic power and transmits it by microwaves to an Earth-receiving antenna. Assuming the sun line direction constant at different seasons (i.e. autumn/spring equinoxes and winter and summer solstices), previous studies have shown the existence of a family of displaced ecliptic orbits above or below the equatorial plane of the Earth around a GEO. In this study, the position of the Sun is assumed on the ecliptic plane with a mean obliquity (inclination of Earth's equator with respect to the ecliptic) of 23.5°. A linear solution as an initial condition for the full equations of motions about a GEO, which yields bounded orbit for the sunlight reflector about the MTS in the Earth-satellite two-body problem with solar radiation pressure. To redirect the sunlight to the MTS, the law of reflection is satisfied by the space mirror attitude.

1. Introduction

In the last decades, alternative energy sources have been proposed to minimize the greenhouse gases effects. Among these, solar energy is the first energy source in the world. However, any solar energy collection system is severely limited by the diurnal day-night cycle. In this manner, previous studies have proposed a solar-power system, consisting of a single large light-weight solar reflector (or a constellation of small solar reflectors), that collects solar energy, even at night, orbiting on a low Earth orbit (LEO) or a geostationary orbit (GEO), instead of collecting solar power by using solar panels on Earth's surface [1], [2], [3], [4]. Note that this kind of space system implies large amounts of solar energy being transported from orbit thousands of miles above Earth's surface. To minimize the problems with energy transportation, a satellite formation flying formed by a sunlight reflector and a microwave transmitting satellite (MTS) on a common GEO, has been presented by several authors [5], [6], [7] [8]. Thus, this Solar Power Satellite (SPS) system would use a space mirror to reflect the solar power energy to an energy generator-transmitter (collector) placed on a nominal geostationary orbit, which would transmit it to any Earth-receiving antenna, reducing the problems with energy transportation.

Takeichi et al. [9] present an Earth-pointing MTS on a common GEO and Sun-pointing reflectors that use the component of sunlight reflector acceleration perpendicular to the Earth's equatorial plane to levitate few kilometers above or below the equatorial plane and achieve orbits parallel to the GEO and have the same radius. However, due to the component of sunlight reflector acceleration parallel to the Earths equatorial plane is not enough to maintain such light levitation [10], [11], the SPS system proposed by Takeichi et al. needs a continuous orbital control by thrusters to maintain the longitude of the system [9] [12]. In this manner, Baig and McInnes [13] showed recently that, using this parallel component of reflector acceleration, it is possible to obtain a family of displaced ecliptic orbits for space mirrors, parallel to the equatorial plane, around a GEO point, i.e. periodic orbits with respect to an Earth-fixed rotating frame at a GEO point. Although, Takeichi et al. [9] and Baig and McInnes [13] show that displaced orbits are feasible, these results are only valid for a few days motion since the sun-line direction is assumed constant at different seasons (equinoxes and solstices). This approximation also permits to find analytical solutions for the linear equations of motion around a GEO point [13], and maintain the sunlight reflector attitude constant along the displaced ecliptic solution.

In this paper, the position of Sun is considered on the ecliptic (Earth's orbit plane), assuming a a mean obliquity equal to 23.5°, and the MTS on a GEO point. In this more realistic model, only numerical solutions exists, and the space mirror orientation satisfies the law of reflection to redirect the sunlight to the MTS along the solutions, i.e. the sunlight reflector pitch angle is no longer constant. Thus, this work uses the linear approximation found by Baig and McInnes [13] as an initial condition for the full equations of motion of the sunlight reflector about the GEO point in the Earth-satellite two-body problem, taking into account the effects solar radiation pressure. Bounded orbits for the SPS system are computed.

2. Equations of motion

A MTS on a common GEO moves around the Earth in a high circular orbit ($42,164.1696$ km measured from the center of the Earth), directly above the equator with a zero angle of inclination, and with an orbital period τ_e equal to the Earth's rotation period, i.e. $\tau_e = 23$h, 56 min, 4.1 s $= 86,141.1$ s [13]. Therefore, the MTS (or any object on a GEO) seems to be fixed regardless of any ground observer.

Consider an Earth-centered, Earth fixed rotating reference system $E\,(x_e, y_e, z_e)$ that rotates with constant angular velocity $\boldsymbol{\omega}_e = \omega_e \hat{\boldsymbol{z}}_e$ ($\omega_e = \frac{2\pi}{\tau_e}$) with respect to an Earth-centered inertial frame system $I\,(x_I, y_I, z_I)$, both with common origin O at the Earth's center of mass, as shown in Fig. 1. Thus, a common GEO becomes a fixed point (GEO point) with respect to the rotating reference system $E\,(x_e, y_e, z_e)$. As shown in Fig. 1, the $x_e - y_e$ and $x_I - y_I$ planes coincide with the equatorial plane of the Earth, and the z_e

and z_I axes are aligned with the Earth's rotational axis. Furthermore, the x_I axis points in the vernal equinox direction, and the x_e axis points to the GEO point and coincides with the x_I axis at $t = 0$. Assuming the gravitational parameter, the magnitude of the angular velocity ω_e and the distance r_{gs} between the Earth's center and GEO point equal to unity, the nondimensional vector equation of motion for an ideal (i.e. perfectly reflecting) space mirror can then be written with respect to the rotating frame as [14]

$$\frac{\mathrm{d}^2\mathbf{r}}{\mathrm{d}t^2} + 2\boldsymbol{\omega}_e \times \frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t} + \nabla U = \boldsymbol{a}, \tag{1}$$

where $\mathbf{r} = (x, y, z)^T$ denotes the position vector of the sunlight reflector with respect to the Earth's center of mass, as shown in Fig. 1. The two-body pseudopotential U is defined as $U = V + \varphi$, where V denotes the gravitational potential due to a perfectly spherical Earth and φ is the centrifugal potential in the rotating frame, which are given by $V = -\frac{1}{r}$, and $\varphi = -\frac{x^2+y^2}{2}$. The solar radiation pressure $\boldsymbol{a}$ in Eq. (1) is defined by $\boldsymbol{a} = \kappa\left(\hat{\boldsymbol{S}}(t) \cdot \boldsymbol{u}\right)^2 \boldsymbol{u}$, where κ is the reflector characteristic acceleration, $\boldsymbol{u}$ is the reflector normal unit vector, and $\hat{\boldsymbol{S}}(t)$ is the unit-vector in the direction of the sun-line. Eclipse seasons, i.e. shadow effects, on geostationary satellites have not be included in this work.

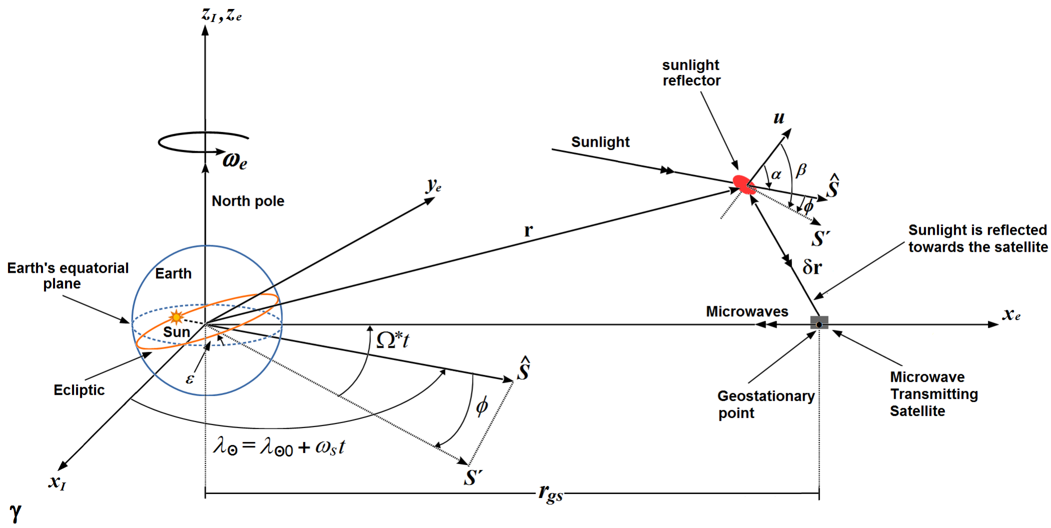

Figure 1. Rotating reference system $E(x_e, y_e, z_e)$ and inertial frame system $I(x_I, y_I, z_I)$, both with common origin O at the Earth's center of mass

Takeichi et al. [9] and Baig and McInnes [13] assumed the sun line $\hat{\boldsymbol{S}}(t)$ at a constant angle ϕ over one period. In this work, a more realistic expression for the solar perturbation $\boldsymbol{a}$ is computed, considering the path of the Sun on the ecliptic. The equatorial components of the sunline with respect to the inertial frame $I(x_I, y_I, z_I)$ are $(-\cos\lambda_\odot, -\cos\varepsilon\cos\lambda_\odot, -\sin\varepsilon\cos\lambda_\odot)^T$, where $\varepsilon = 23.5°$ is the mean Earth's ecliptic and $\lambda_\odot = \lambda_{\odot 0} + \omega_s t$ is the longitude of the Sun and $\lambda_{\odot 0}$ is the initial solar longitude as shown in Fig. 1 [15]. The sunline $\hat{\boldsymbol{S}}(t)$ in the rotating frame $E(x_e, y_e, z_e)$ can be computed as

$$\hat{\boldsymbol{S}}(t) = \begin{pmatrix} \cos t & \sin t & 0 \\ -\sin t & \cos t & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} -\cos\lambda_\odot \\ -\cos\varepsilon\cos\lambda_\odot \\ -\sin\varepsilon\cos\lambda_\odot \end{pmatrix} = \begin{pmatrix} \hat{S}_\xi(t) \\ \hat{S}_\eta(t) \\ \hat{S}_\zeta(t) \end{pmatrix}. \quad (2)$$

The sunlight must be redirected towards the MTS, i.e. the reflected sunlight vector must be equal to $-\delta\mathbf{r}$, as shown in Fig. 1. Therefore, the law of reflection requires that [16]

$$\boldsymbol{u} = \frac{\hat{\boldsymbol{S}}(t) + \hat{\delta}\mathbf{r}_{sr}}{\left|\hat{\boldsymbol{S}}(t) + \hat{\delta}\mathbf{r}_{sr}\right|} \quad (3)$$

Equations of motion, Eq. (1) can now be integrated numerically. To investigate bounded solutions for Eq. (1) about the GEO point, the linear ecliptic orbits found by Baig and McInnes [13] are used as initial conditions. Considering a GEO point at $\mathbf{r}_{gs} = (1, 0, 0)^T$, then the position vector $\mathbf{r}$ of the sunlight reflector can be written as $\mathbf{r} = \mathbf{r}_{gs} + \delta\mathbf{r}$, where $\delta\mathbf{r} = (\xi, \eta, \zeta)^T$ is the reflector position vector with respect to the GEO point (see Fig. 1). Assuming a constant attitude for the reflector pitch angle, a linear planar ecliptic orbit is given by [13]

$$\xi(t) = -\kappa\left(\frac{2\Omega^* + \Omega^{*2}}{\Omega^{*4} - \Omega^{*2}}\right)\cos^2\alpha\cos\beta\cos(\Omega^* t), \quad (4)$$

$$\eta(t) = \kappa\left(\frac{\Omega^{*2} + 2\Omega^* + 3}{\Omega^{*2} + 2\Omega^*}\right)\left(\frac{2\Omega^* + \Omega^{*2}}{\Omega^{*4} - \Omega^{*2}}\right)\cos^2\alpha\cos\beta\sin(\Omega^* t), \quad (5)$$

where $\zeta(t) = 0$, α is the reflector pitch angle (i.e. $\cos\alpha = \hat{\boldsymbol{S}}(t) \cdot \boldsymbol{u}$), ϕ is the inclination angle for the sun-line above the Earth's equatorial plane, $\beta = \alpha + \phi$ is the angle that the reflector normal makes with the equatorial plane of Earth, as shown in Fig. 1, and $\Omega^* = 0.9973$ is the nondimensional angular velocity of the rotating frame relative to the sun-line [13].

Figure 2 shows a numerical simulation of the variation of the sunlight reflector relative position coordinates with a characteristic acceleration $\kappa = 0.018$ mms^{-2} during one years span. The linear solutions, Eqs. (4)-(5), were used as initial conditions in the numerical simulation with $t = 0$, $\phi = 0$, $\alpha = 0$, $\phi = 0$ and $\lambda_{\odot 0} = 180°$, such that the sun-line is aligned with the vernal equinox at $t = 0$. Figures 2(a)-(c) show a bounded behavior of the reflector orbit with respect to the MTS. However, the motion is strongly affected by the solar perturbation. Figure 2(d) shows the variation of the reflector pitch angle α (i.e. control history) when the law of reflection is applied in the space mirror attitude along the time. Finally, Figs. 3(a)-(c) and Fig. 3(d) show the bounded orbits for the reflector with respect to the GEO point in the rotating frame, respectively.

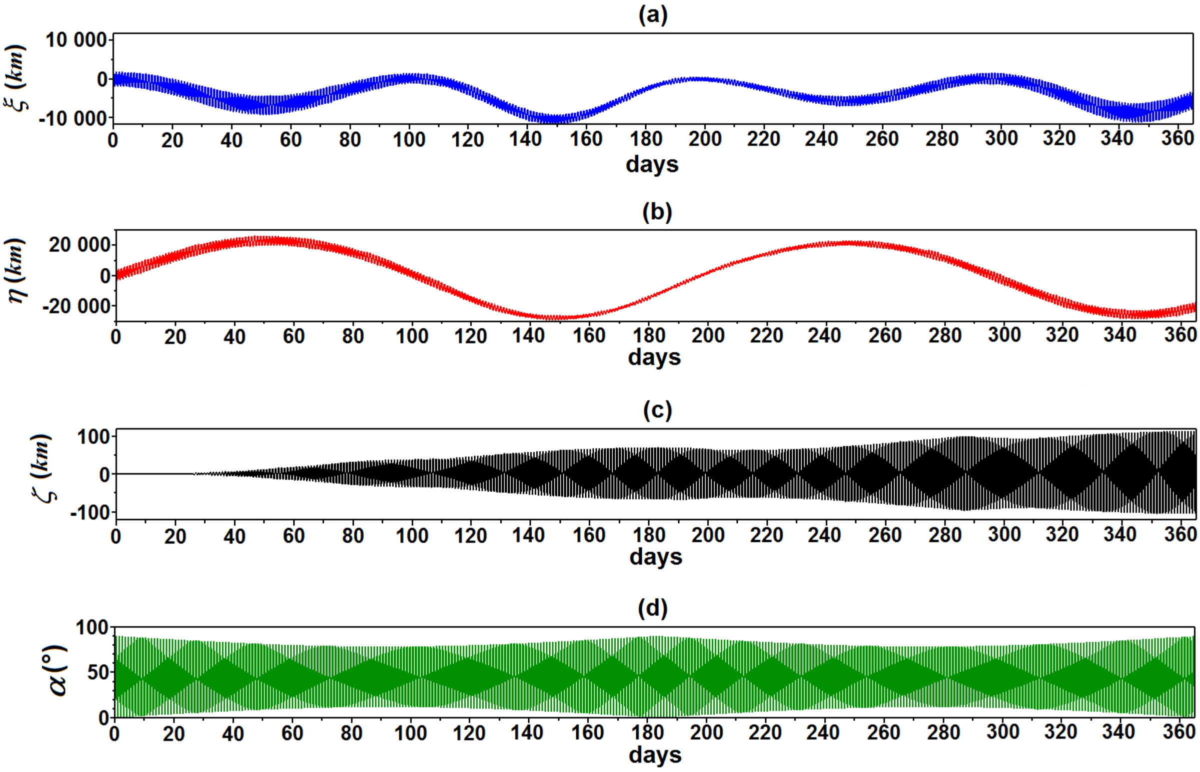

Figure 2. (a)-(c) Variation of the sunlight reflector relative position coordinates with a characteristic acceleration $\kappa = 0.018$ mms^{-2} during one year span. (d) Variation of the reflector pitch angle α (i.e. control history)

3. Conclusions

In this study a SPS system have been investigated considering a space mirror and a MTS in formation around a GEO point with respect to an Earth-centered rotating frame that rotates with the same angular velocity of the Earth. In order to include the direction of the sun-line, the position of the Sun was approximated by a circular ecliptic trajectory, assuming a mean inclination of Earth's equator with respect to the ecliptic equal to 23.5°. To redirect the sunlight to the MTS, the law of reflection was applied in the reflector attitude, so that a bounded orbit for the sunlight reflector was obtained using as initial conditions the ecliptic orbits found in a linear approximation with constant attitude for the reflector pitch angle. As was noted, solar perturbation affected the synchronization of the SPS system, increasing the longitude and producing large variations of the reflector pitch angle. The possibility of reducing the longitude of the SPS system and the variation of the reflector pitch angle using a continuous orbital control by thrusters or a tethered system will be considered in future studies.

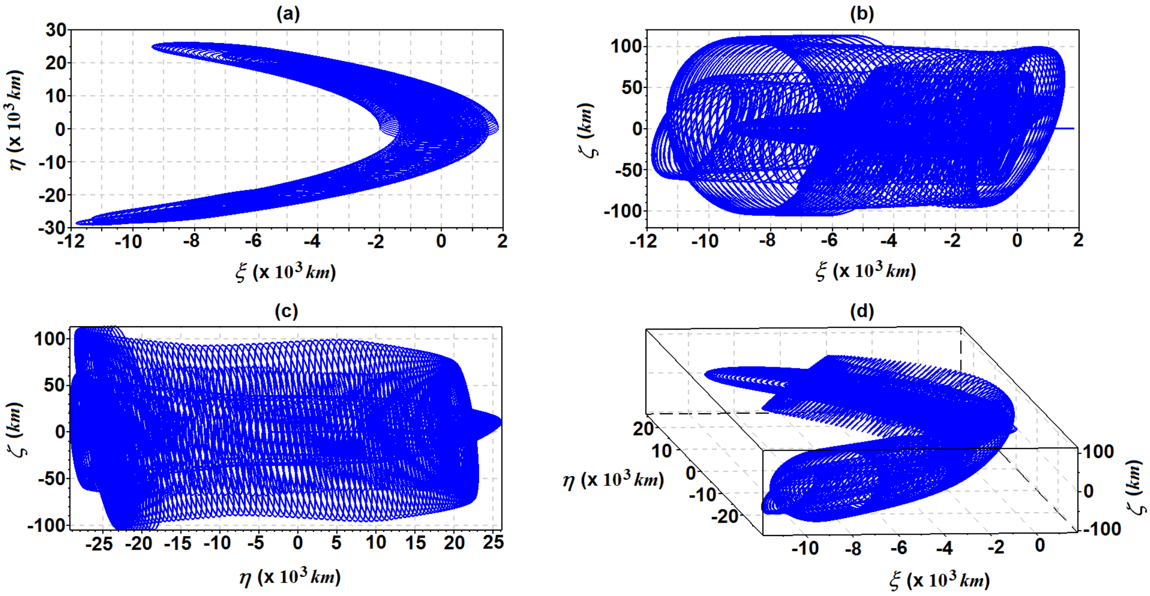

Figure 3. (a)-(c) Projections in the $\xi - \eta$, $\xi - \zeta$, and $\eta - \zeta$ planes for the sunlight reflector motion in the rotating frame corresponding to the relative position vectors in Fig. 2. (d) Bounded orbit for the sunlight reflector in the rotating frame.

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