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Loosely-displaced geostationary orbits with hybrid sail propulsion

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ABSTRACT

To overcome the congestion of geostationary orbit slots, previous work proposed to use vertically-displaced, non-Keplerian geostationary orbits by means of continuous low-thrust propulsion in the form of hybrid solar sail and solar electric propulsion (hybrid sail). This work extends and generalizes that concept by loosening the position constraint and introducing a station-keeping box. Sub-optimal orbits are first found with an inverse method that still satisfy the geostationary position constraint (i.e., no station-keeping box), which will be referred to as ideal displaced geostationary orbits. For these sub-optimal orbits, it is found that the hybrid sail saves propellant mass compared to the pure solar electric propulsion case: for solar sail lightness numbers of up to a value of 0.2 and the most favorable time during the year (i.e., at summer solstice), the hybrid sail saves up to 71.6% propellant mass during a single day compared to the use of pure solar electric propulsion. Subsequently, the sub-optimal orbits are used as a first-guess for a direct optimization algorithm based on Gauss pseudospectral transcription, which loosens the position constraint. This enables a more flexible trajectory around the ideal displaced geostationary orbit and lets the solar sail contribute more efficiently to the required acceleration. It therefore leads to a further propellant savings of up to 73.8%. Finally, the mass budget shows that by using by using far-term solar sail technology, the hybrid propulsion system enables an evident reduction in the required initial mass of the spacecraft for a given payload mass with a relatively long mission duration.

1. Introduction

The geostationary orbit (GEO) is a circular, equatorial orbit whose period equals the Earth's rotational period and its orbital radius therefore equals approximately 42,164 km. It allows a satellite to be stationary above a certain point on the Earth's equator. With the advantage of being stationary, GEO satellites are largely used for telecommunications and Earth observation (mainly meteorology). The GEO is a unique and currently very congested orbit, especially at longitudes above densely populated areas [1].

Highly non-Keplerian orbits (NKOs) are trajectories that can be achieved by a continuous control acceleration generated by the spacecraft, which was systematically introduced by McKay et al. [2]. By partially offsetting or complementing the effects of gravity, NKOs show evident advantages in that new orbits can be designed. The design [4–10], optimization [4–10], stability and control [11–13] of NKOs have been researched extensively; proposed applications range from pole-sitters [3,4], lunar far-side communication and lunar south-pole coverage [5–7], Mars, Mercury and Venus remote sensing [7,8], further Mars exploration [9], to near-Earth asteroids rendezvous [10]. The concept of using an NKO to displace the GEO has already been proposed [1] and the existence of light-levitated GEOs for solar sailing has already been shown by Baig and McInnes [14]. This paper studies the optimal design of loosely-displaced GEOs and proposes the use of solar sail propulsion and solar electric propulsion (SEP) on the same spacecraft (hybrid sail propulsion).

Although solar sailing is a relatively old notion, it has many high-demanding technology requirements on materials, control and structures [15]. Only recently, three small sail demonstrator missions were deployed: one by JAXA, the Interplanetary Kite-Craft Accelerated by Radiation of the Sun (IKAROS); one by NASA, NanoSail-D2; and one by The Planetary Society, LightSail-1 [16–18]. In addition, the NEA Scout mission plans to launch a CubeSat-sized spacecraft propelled by a solar sail for near-Earth asteroid exploration mid-2018 [19]. Much research has focused on using solar sailing as the primary propulsion system on a spacecraft to maintain NKOs [20–23]. However, there are still some

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challenges to overcome, such as the difficulties of designing and building large and lightweight membrane structures. In addition, the solar sail is unable to generate a thrust component towards the Sun [15]. Compared to solar sailing, SEP relies on a finite onboard propellant source, but is a much more mature and near-term technology. It can produce a relatively low thrust with high specific impulse. It has been successfully used in several space missions, including Deep Space 1 (1998) [24], the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE, 2009) [25], and SMART-1 [26].

Considering the complementarity of solar sailing and SEP, the concept of hybridizing a relatively small, near-term solar sail and SEP has been previously proposed [3,27]. In this field, research is flourishing, aiming to maximize the potential of the hybrid sail propulsion system. Proposed concepts include optimal transfers from Earth to Venus and Mars [28,29], optimal trajectories for Earth pole-sitters [3,4], pole-sitters at other planets [8], and displaced orbits in the Earth–Moon system [30]. As those studies show, the hybrid sail has better performance in terms of long-term propellant consumption than pure SEP and lower technological challenge than a large solar sail, at the cost of increased system and control complexity.

In this work, a generalization of the hybrid-sail displaced geostationary orbit (DGEO) proposed by Heiligers et al. [1] is presented and discussed. We relax the constraint of a constant relative position with respect to an Earth observer, while keeping the spacecraft in an assigned station-keeping box, generating a loosely-displaced GEO (LDGEO). It is expected that, by releasing the constraint on the position, additional propellant can be saved by the hybrid sail/SEP combination. We indeed show that propellant can be saved, because the station-keeping box allows the orbit to be tilted which allows the solar sail to operate more efficiently and therefore reduces the total SEP thrust required. However, the introduction of the concept of a station-keeping box comes with the drawback that the spacecraft is not perfectly stationary above a point on the Earth, and thus not truly "geostationary". This could cause potential pointing problems. However, we show that, if the station-keeping box is small enough, the effects of pointing problems can be restricted to an acceptable level such that this displacement will not be perceivable from Earth.

The remainder of the paper is organized as follows: after a brief description of the hybrid sail dynamics (Sec. II), Sec. III explains the concept of the DGEO. It then presents an inverse method to minimize the SEP thrust and obtain the corresponding solar sail control for an ideal DGEO, i.e., without a station-keeping box. Those results are subsequently used as a first-guess for a Gauss-pseudospectral algorithm that does include a station-keeping box, which solves the optimal control problem numerically. Finally, Sec. IV discusses the optimal mass budget for a hybrid sail spacecraft for different sail sizes and mission lifetimes.

2. Equations of motion

The ideal DGEO is an NKO which is parallel to the equatorial plane (above or below) and whose period equals the Earth's rotational period. Compared to the distance from the Sun, a spacecraft in a DGEO is much closer to the Earth. Therefore, the dynamics are defined as two-body, Earth-centered dynamics, neglecting perturbations from the higher order harmonics from the Earth's potential, the Moon, Sun, and so on. A rotating reference frame, $A(X, Y, Z)$ is considered in which the origin is at the center of the Earth; the X axis points towards the ideal DGEO satellite's projection on the equatorial plane; the Z axis is aligned with the angular momentum vector of the Earth and perpendicular to the equatorial plane, and the Y axis completes the right-handed Cartesian reference frame (see Fig. 1). In the following, all vectors are expressed

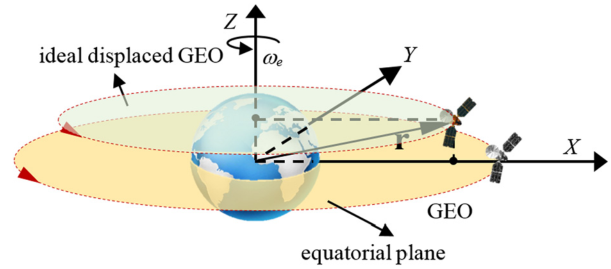

Fig. 1. DGEO in the rotating reference frame (A).

in this frame unless specified by a different superscript. The equations that describe the motion of the spacecraft in the rotating reference frame are

$$\begin{cases} \ddot{x} = 2\omega_e \dot{y} + \omega_e^2 x - \dfrac{\mu_e x}{r^3} + a_X \\ \ddot{y} = -2\omega_e \dot{x} + \omega_e^2 y - \dfrac{\mu_e y}{r^3} + a_Y \\ \ddot{z} = -\dfrac{\mu_e z}{r^3} + a_Z \end{cases} \tag{1}$$

Considering the X, Y and Z axes, the spacecraft position vector is $\mathbf{r} = [x, y, z]^{\mathrm{T}}$, $r = \|\mathbf{r}\|$, ω_e is the Earth's constant angular velocity and μ_e is the gravitational parameter of the Earth. Furthermore, a thrust-induced acceleration $\mathbf{a} = [a_X, a_Y, a_Z]^{\mathrm{T}}$ is assumed to maintain the DGEO. For a hybrid sail propulsion system, $\mathbf{a}$ consists of two parts, which can be written as

$$\mathbf{a} = \mathbf{a}_{\mathrm{S}} + \mathbf{a}_{\mathrm{SEP}} \tag{2}$$

where $\mathbf{a}_{\mathrm{S}}$ is the contribution of the solar sail and $\mathbf{a}_{\mathrm{SEP}}$ is the contribution of the SEP thruster.

Because frame (A) rotates at the same angular speed as the Earth's rotation, the DGEO is represented by a stationary point. Therefore, the spacecraft's position with respect to the Y axis, the velocity $\dot{\mathbf{r}} = [\dot{x}, \dot{y}, \dot{z}]^{\mathrm{T}}$ and the acceleration $\ddot{\mathbf{r}} = [\ddot{x}, \ddot{y}, \ddot{z}]^{\mathrm{T}}$ are all equal to 0. Then, the equilibrium solutions can be obtained by eliminating the motion-related terms from Eq. (1):

$$\begin{cases} a_X = -\omega_e^2 x + \dfrac{\mu_e x}{r^3} \\ a_Y = 0 \\ a_Z = \dfrac{\mu_e z}{r^3} \end{cases} \tag{3}$$

Let us consider an inertial reference frame, $I(X^{(I)}, Y^{(I)}, Z^{(I)})$, with the origin at the Earth's center; the $X^{(I)}$ axis is aligned with the projection of the Sun–Earth vector on the equatorial plane *at* winter solstice; the Z_I axis is aligned with the angular momentum vector of the Earth and perpendicular to the equatorial plane, and the $Y^{(I)}$ axis completes the right-handed Cartesian reference frame. In that frame, the ideal DGEO is a circle with a constant radius from the $Z^{(I)}$ axis and at constant distance from the $X^{(I)}$–$Y^{(I)}$ plane, i.e. parallel to the equatorial plane (see Fig. 2). The magnitude and direction of the acceleration required to maintain the NKO are constant in frame (A), see Eq. (3), and therefore conduct a rotation once per DGEO period in frame (I), see the arrows in Fig. 2.

2.1. Solar sail propulsion

Solar sails can produce continuous accelerations without any propellant consumption. In this work, a perfect solar sail force model will be used, which only accounts for specular reflection. Note that, in reality, the efficiency of the sail will be less than that

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