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Dynamical study of low Earth orbit debris collision avoidance using ground based laser

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Collision avoidance

Abstract The objective of this paper was to investigate the orbital velocity changes due to the effect of ground based laser force. The resulting perturbations of semi-major axis, miss distance and collision probability of two approaching objects are studied. The analytical model is applied for low Earth orbit debris of different eccentricities and area to mass ratio and the numerical test shows that laser of medium power ~5 kW can perform a small change $\Delta\overline{V}$ of an average magnitude of 0.2 cm/s which can be accumulated over time to be about 3 cm/day. Moreover, it is confirmed that applying laser $\Delta\overline{V}$ results in decreasing collision probability and increasing miss distance in order to avoid collision.

1. Introduction

During the recent years, functional satellites are threatened by enormous number of space debris which increases dramatically as the use of space expands. Radar and optical surveillance systems, as well as direct impact measurements, show that there are a huge number of debris in low Earth orbits of about 1–10 cm size. In frame of orbital debris removal, several broad research efforts have been performed. The majority of these researches were based on vaporization or ablation of these small objects using different ground based laser systems in order to permit debris re-entry. However, building and operating of such systems are the most cost effective way to mitigate the debris problem (Phipps et al., 2012; Campbell et al., 2000; Choi and Pappa, 2012).

In comparison of those schemes that aimed to de-orbiting debris using laser powers, laser collision avoidance maneuver requires much less force and less sophisticated laser systems. The application of small change ΔV results in lowering or rising of semi-major axis and orbital period allowing rapid along-track displacement to grow over time. This causes the two approaching objects to miss each other in time even if the orbital elements remain essential unchanged Stupl et al. (2010).

Many authors studied the feasibility of using a medium power laser of about 5–10 kW to avoid fraction of collisions in low Earth orbit (Stupl et al., 2010; Mason et al., 2011).

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The main issue of this paper is to represent a dynamical study of using ground based laser as debris collision avoidance tool. This work is organized as follows: Section 2 represents the analytical modeling of the problem which includes the formulation of light force and orbital velocity changes using a geocentric equatorial coordinate system in addition to miss distance and collision probability. Section 3 represents the numerical applications and the general conclusion.

2. Laser collision avoidance

2.1. Laser beam propagation

For standard atmospheric conditions, only linear mechanism of laser atmospheric interactions is considered. Atmospheric turbulences are countered by using the adaptive optics and technical capabilities of the laser system. Based on the previous postulates, the laser intensity delivered to the debris surface is determined using an analytical model in which laser intensity is proportional to the laser power and inversely to debris altitude and laser divergence. This laser intensity is given by El-Saftawy et al. (2007) and Khalifa (2009):

$$S(\rho) = \frac{P}{\pi\theta^2 \rho^2_{\text{debris}}} \text{Exp} - \left[\left[\frac{\sigma^{\text{mol}}_{\text{scat}}(0)h}{\sin(\phi)}\right]\left[1 - \text{Exp}\left(-\frac{\rho\sin(\phi)}{h}\right)\right] + \sigma^{\text{aer}}_{\text{scat}}(\rho)\right], \tag{1}$$

where ρ_{debris} is the debris altitude, P is the laser power, θ is the beam divergence, ϕ is the elevation angle, $\sigma^{\text{mol}}_{\text{scat}}(0)$ is the molecule scattering coefficient at sea level, $\sigma^{\text{aer}}_{\text{scat}}$ is the aerosols scattering coefficient and h is the sea level altitude. ρ is considered to be the first 50 km of the Earth's atmosphere which is considered as the most effective on the beam propagation Danielson et al. (2003).

2.2. Laser force

The total radiant force exerted on a flat non-perfectly reflecting surface is given by Mc Innes Colin (1999):

$$\bar{f} = \frac{SA}{C}\psi\hat{m} \tag{2}$$

where

$$\psi = \left[4\rho'\beta\cos^4\eta + 2(1+\rho'\beta)\left(B_f\rho'(1-\beta) + \alpha'\frac{\varepsilon_f B_f - \varepsilon_b B_b}{\varepsilon_f + \varepsilon_b}\right)\cos^3\eta + \left\{\left(B_f\rho'(1-\beta) + \alpha'\frac{\varepsilon_f B_f - \varepsilon_b B_b}{\varepsilon_f + \varepsilon_b}\right)^2 + (1-\rho'\beta)^2\right\}\cos^2\eta\right]^{1/2} \tag{3}$$

where $\hat{m}$ is a unit vector directed through the force direction, c is the speed of light and S is the radiation intensity at debris surface, η is the radiation incident angle on debris surface normal, β is debris surface specularity, ρ' is debris surface reflectivity, B_f and B_b are the non-Lambertian coefficient of front and back debris surfaces respectively, α' is debris absorption coefficient, and ε_f and ε_b are front and back debris surface emissivity, respectively. ψ can take a value from 1 to 2, where $\psi = 0$ means that the object is translucent, $\psi = 2$ means that all photons are reflected and for the object that absorbs all of the incident radiation $\psi = 1$.

For non-perfectly reflecting surfaces, The force vector, $\hat{m}$, is not directed normal to the surface. But, it inclines by an angle ϑ, known as the cone angle, to the incident direction, $\hat{\rho}_{\text{debris}}$. Then, force components in the incident direction will be:

$$\bar{f}_{\rho_{\text{debris}}} = \frac{SA}{C}\psi\cos\vartheta\hat{\rho}_{\text{debris}}. \tag{4}$$

2.3. Coordinate systems

The geocentric equatorial system is used with the unit vectors; $\hat{e}_x$ directed parallel to the Earth equatorial plane, $\hat{e}_y$ directed in the plane that contains the meridian of the sub-debris point and $\hat{e}_z$ directed normal to the equatorial plane. As shown in Fig. 1, the incident radiation vector, $\bar{\rho}_{\text{debris}}$, is given by:

$$\bar{\rho}_{\text{debris}} = \bar{r} - \bar{r}_E, \tag{5}$$

where $\bar{r}$ is debris position vector and $\bar{r}_E$ is the Earth radius vector (station coordinates). For an oblate Earth, the Earth radius vector is given by Escobal (1965):

$$\bar{r}_E = \begin{bmatrix} G_1\cos\varphi_g\cos\tau \\ G_1\cos\varphi_g\sin\tau \\ G_2\sin\varphi_g \end{bmatrix}, \tag{6}$$

with

$$G_1 = \frac{a_e}{\left(1-(2f'_e - f'^2_e)\sin^2\varphi_g\right)^{1/2}} + h, \qquad G_2 = \frac{a_e(1-f'_e)^2}{\left(1-(2f'_e - f'^2_e)\sin^2\varphi_g\right)^{1/2}} + h, \tag{7}$$

where a_e is the Earth's Equatorial radius, f'_e is the Earth's flattening, φ_g is the geodetic latitude, h is the height above sea level and τ is the sidereal time.

The debris position vector, $\bar{r}$, in the geocentric coordinate system, is given by Escobal (1965):

$$\bar{r} = r\begin{pmatrix} \cos\Omega\cos(\omega+\upsilon) - \sin\Omega\sin(\omega+\upsilon)\cos i \\ \sin\Omega\cos(\omega+\upsilon) + \cos\Omega\sin(\omega+\upsilon)\cos i \\ \sin(\omega+\upsilon)\sin i \end{pmatrix}, \tag{8}$$

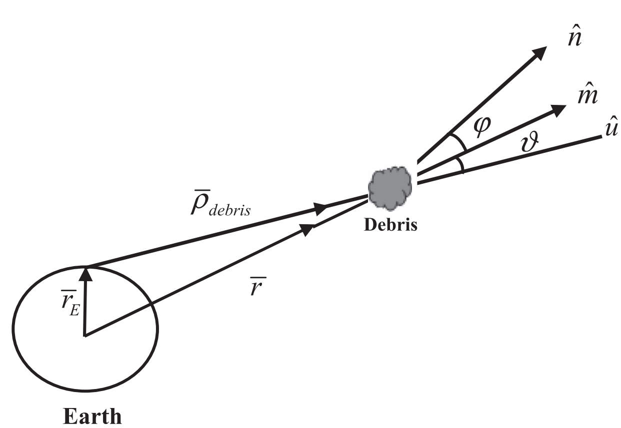

Figure 1 Ground based laser beam fires toward debris.