Energy Variation of Space Debris Considering Orbital Maneuvers and Ground-based Laser

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Abstract: -The frequency of space debris incidents is on the rise, particularly in regions where there are critical densities, elevating the risk of collisions. Ground-based lasers, when precisely targeted, have the potential to induce propulsion effects that can alter the perigee of debris particles. This alteration facilitates their swift incineration upon reentry into Earth's atmosphere or enables adjustments to their orbital trajectories. The objective was to assess the effectiveness of orbital maneuvers, considering gravitational influences alongside the utilization of ground-based lasers. We focused on space debris ranging from 1 cm to 10 cm in size, orbiting at altitudes between 100 and 1000 km, as they approach Earth within a hypothetical heliocentric orbit. Through our analyses, we examined variations of velocity and energy following close approaches, employing single-pulse laser propulsion. This investigation is crucial for evaluating the orbital characteristics of space debris, contributing to safe reentry into Earth's atmosphere and collision avoidance through precise impulse application by ground-based lasers. Our analytical model factors in laser fluence, debris attitude, and the relative motion between the laser and debris. Our results indicate that the laser induces minor changes in delta-V, with maximum energy efficiency that can be harnessed to enhance reentry energy. Consequently, it is possible to achieve a 30%increase in the variation of orbital elements after the maneuver. This study thus offers a comprehensive examination of such maneuvers, highlighting their advantages over traditional orbital adjustments and outlining optimal conditions for collision avoidance and space debris mitigation. We recommend further enhancing dynamic modeling and validating experimental outcomes to refine our understanding of these studies.

Keywords: Space Debris, Orbital maneuvers, ground-based laser, Astrodynamics.

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1. Introduction

The proliferation of spacecraft in Earth's orbit has reached a concerning level, posing a significant threat to future space missions. Since 1961, a multitude of objects has been orbiting the Earth, resulting in a substantial challenge with spacecraft and space debris. This accumulation of rocket bodies and payloads has led to the orbiting mass exceeding 9,300 tonnes. Currently, there have been over 6,050 launches, resulting in approximately 56,450 tracked objects in orbit, with around 28,160 remaining (IADC (2024)).

As the number of fragments continues to rise, collisions between them become increasingly frequent, creating a hazardous scenario known as the "Kessler Syndrome" (Kessler and Cour-Palais., 1978) and (Kessler, 1990). This syndrome presents a critical dilemma where debris collisions can trigger a chain reaction, further amplifying the amount of space debris. Addressing this issue is crucial by implementing strategies to prevent the creation of more debris and actively remove existing debris from Earth's orbit. One effective approach is through orbital maneuvers. Moreover, the references to studies by (Ledkov and Aslanov, 2022) and (Svotina and Cherkasova, 2023) suggest that these works contribute to our understanding of space debris mitigation. However, it would be advantageous to provide more detailed insights into the specific contributions of these studies to offer a clearer perspective on how they align with the overall discourse on this topic.

The space debris, congregate in specific regions around our planet, such as low Earth orbit and semi-synchronous orbit. As the quantity of these objects continues to mount, so does the risk of collisions with operational spacecraft. This risk escalates annually as the likelihood of encountering new debris rises, contingent upon its orbital trajectory and velocity.

Heliocentric Earth Orbit (HEO) missions represent important missions in space exploration, where spacecraft journey beyond Earth's orbit to explore distant planets or observe the depths of space. However, what many may not realize is that these missions often leave behind rocket stages, equipment, or satellites in orbits with both significant Earth-centric and heliocentric components. This creates the potential for space debris to accumulate in HEO, posing hazards to future missions and the broader space environment. Similar to debris in other orbits, this space junk poses collision risks to operational spacecraft and satellites. Thus, it is imperative to meticulously monitor and manage the presence of debris in HEO to minimize collision risks and safeguard the integrity of space missions. An example highlighting the importance of studying debris in heliocentric orbits is the case of the third stage of the Apollo Saturn-V, likely from the Apollo 12 mission, which ended up in an endless heliocentric orbit near Earth. This incident underscores the significance of monitoring debris in heliocentric orbits, as it can unpredictably approach our planet. Therefore, as humanity continues its exploration of space, vigilance regarding debris in Heliocentric Earth Orbit remains paramount.

In contemporary aerospace activities, engineers have devised ingenious methods to mitigate collisions and reduce space debris by employing spacecraft maneuvering in orbit. This technique involves altering the spacecraft's energy to modify its trajectory, often leveraging gravitational forces without additional propulsion—a method known as swing-by maneuvering. This approach has been widely employed by mission designers to enhance launch efficiency and expedite spacecraft journeys. Notable studies by (Prado and Broucke, 1995),(Formiga and Prado, 2015), and (Gomes *et al.*, 2016) have significantly contributed to our understanding of swing-by maneuvers' effectiveness. The success of this technique in missions like Voyager I and II and Pioneer 10 underscores its efficacy in exploring the outer reaches of our solar system. Additionally, alternative orbit-changing methods explored in the literature, such as those discussed by (Marchal, 1965) and (Gobetz and J.R., 1969), further enrich our understanding of spacecraft maneuverability in orbit.

The utilization of Laser Beam Orbital Debris Removal (LODR) emerges as a cost-effective strategy to tackle the escalating challenge of space debris (Phipps, 2012). This method holds promise for enhancing ephemeris precision and effecting orbit modifications for substantial objects. LODR involves precisely targeting and irradiating small debris objects in orbit using high-powered laser beams. Upon interaction with the laser beam, the debris's surface is heated, leading to vaporization or ablation, generating a thrust force that alters the debris trajectory, facilitating its harmless re-entry into the Earth's atmosphere. Introduced approximately two decades ago, this concept has garnered significant attention for its potential in addressing space debris challenges.

Ground-based lasers offer a practical solution, perturbing the orbits of small debris fragments with minimal energy input (Phipps, 2012). However, the feasibility and limitations of laser power beaming from ground to space are meticulously examined, considering atmospheric constraints and technical counter-measures (Scharring *et al.*, 2021). While photon pressure demonstrates near-term viability, its effectiveness in collision avoidance is constrained by the modest application of force (Scharring *et al.*, 2021). Conversely, laser ablation offers greater force generation potential but poses challenges in predictability (Sinko and Phipps, 2009).

The primary focus of this study is to assess re-entry energy and orbital elements after maneuvers executed by space debris, considering the orientation of the laser pulse, velocity, and approach angle. This underscores the importance of comprehensively analyzing the impact of various factors on resultant energy variations and primarily orbital changes. By integrating these factors, the study aims to elucidate the dynamics involved in space debris mitigation maneuvers, particularly concerning re-entry into Earth's atmosphere.

Furthermore, evaluating re-entry energy and orbital elements facilitates a comprehensive assessment of the effectiveness and feasibility of employing laser pulses for orbital maneuvers and debris removal. It is a critical parameter in understanding the dynamics and potential risks associated with objects returning to Earth's atmosphere and is indispensable for informing future mitigation strategies.

In summary, the exhaustive analysis of re-entry energy and orbital elements, incorporating laser pulse direction and other pertinent parameters, bolsters the scientific rigor and practical relevance of the study's findings in the realm of space debris mitigation and orbital dynamics.

2. Mathematical model

To tackle this problem, a system consisting of three bodies is considered: The Sun (M_1), the Earth (M_2), and the space debris, represented by an infinitesimally massed particle (M_3), initially orbiting the Sun. Subsequently, the debris undergoes a close encounter with Earth. The problem is decomposed into three phases, each modeled as a classic "Two-Body Problem" and encapsulated within the framework of "Patched Conics." The procedure can be divided into three parts: In the initial phase, the study begins with neglecting the gravitational influence exerted by M_2, assuming a Keplerian orbit for M_3 around M_1.Subsequently, in the second phase, as M_3 approaches closer to M_2, it is presumed that M_1 is sufficiently distant from M_2, resulting in the system $M_2 - M_3$ being akin to a new "two-body" problem. This assumption holds true upon M_3 entering the sphere of influence of M_2—the region where M_2 exerts a gravitational force more pronounced than that of M_1. Lastly, the third phase of the patched conics approximation involves once again disregarding the influence of M_2. The system $M_1 - M_3$ is considered anew as a "two-body" problem. This phase initiates as M_3 exits the sphere of influence of M_2. At this juncture, the spacecraft assumes a fresh Keplerian orbit around M_1, signifying the completion of the maneuver.

The encounter induces changes in the space debris orbit relative to the Sun. A standard maneuver can be characterized by three key parameters: ρ_{deb}, representing the minimum distance between the fragment and Earth during closest approach, where h denotes the distance from the fragment to Earth's surface and r_e signifies Earth's radius; V_∞^- and V_∞^+, denoting the velocities of the debris relative to Earth before and after the passage, respectively; and α, the angle of approach, defined as the angle between the line connecting the primaries and the periapsis of the close approach trajectory. The velocity and orbital elements of M_3 undergo alterations due to the close approach with Earth (Santos *et al.*, 2002; Formiga and Prado, 2015).

This paper confines its scope to the two-dimensional case. The spatial coordinates and the velocity of the space debris in this case are defined by the variables illustrated in Fig. 1($\phi = 0^o$).

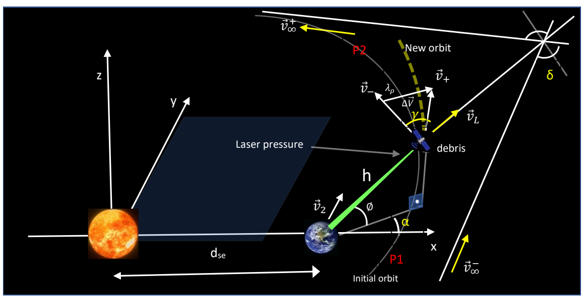


Fig. 1. Swing-by maneuver considering ground-based laser

$$\vec{X} = \begin{bmatrix} d_{se} + \rho_{deb}\cos\alpha \\ \rho_{deb}\sin\alpha \end{bmatrix}, \vec{V} = V_p \begin{bmatrix} -\cos\gamma\sin\alpha \\ \cos\gamma\cos\alpha \end{bmatrix} \quad (1)$$

In the provided context, d_{se} represents the distance between the Sun and the Earth, while ρ_{deb} signifies the distance from the space debris to the center of the Earth (the magnitude of the periapsis radius of the space debris trajectory). V_p denotes the velocity of the space debris relative to Earth at periapsis. Referring to Fig. 1, angles α and ϕ determine the orientation of the periapsis direction, while γ represents the angle between the velocity vector $\vec{V_p}$ and the horizontal plane passing through the periapsis. This formulation, akin to that utilized by (Prado, 1996) and (Formiga and Santos, 2015), allows for the assumption of velocity components as:

$$\vec{V_\infty^-} = V_\infty \sin\delta \begin{bmatrix} \cos\alpha \\ \sin\alpha \end{bmatrix} + V_\infty\cos\delta \begin{bmatrix} -\cos\gamma\sin\alpha \\ \cos\gamma\cos\alpha \end{bmatrix}$$

$$\vec{V_\infty^+} = -V_\infty \sin\delta \begin{bmatrix} \cos\alpha \\ \sin\alpha \end{bmatrix} + V_\infty\cos\delta \begin{bmatrix} -\cos\gamma\sin\alpha \\ \cos\gamma\cos\alpha \end{bmatrix} \quad (2)$$

V_∞ represents the magnitude of the velocity of the spacecraft with respect to the Earth at the moment the approach begins. It can be calculated using the equation $V_\infty^2 = V_p^2 + \frac{2\mu_2}{\rho deb}$, where μ_2 denotes the gravitational parameter of the Earth. Utilizing the principle of energy conservation, it becomes feasible to determine the magnitude of the velocity of the space debris in its periapsis before the impulse $(V-)$ and the velocity of the spacecraft at the periapsis of its orbit after the impulse (V_+) respectively:

$$\mathrm{V}_- = \sqrt{(V_\infty^-)^2 + 2\mu_2/\rho_{deb}};$$
$$V_+ = \sqrt{V_-^2 + \Delta V^2 + 2V_-\Delta V\cos\lambda_\rho} \quad (3)$$

Here, ΔV represents the magnitude of the impulse resulting from laser pressure and gravitational effects. It's worth noting that if $0^o < \lambda < 180^o$, the space debris is directed opposite to the secondary body. Conversely, if $-180^o < \lambda < 0^o$, the space debris is directed towards the secondary body. The angle λ_ρ is determined by:

$$\cos\lambda_\rho = \frac{\Delta V^2 + V_+^2 - V_-^2}{-2V_+V_-} \quad (4)$$

and the deflection angle can be assumed to be (Broucke, 1988)

$$\delta = \sin^{-1}\left[\frac{1}{1 + \frac{\rho_{deb}V_\infty^2}{\mu_2}}\right] \quad (5)$$

3. Energy variation and laser impulse

In this section, we will explore the equations utilized to calculate changes in velocity, energy, impulse induced by the laser, and orbital elements following the maneuver.

As the space debris moves, an impulse will be applied due to laser pressure, denoted as $\Delta V_L \widehat{\rho}$, where $\widehat{\rho}$ represents the direction normal to the reflective surface. This direction defines the vector between the debris and Earth within the rotating system (a unit vector defining the impulse direction relative to the velocity of the space debris). It is important to note that ΔV_L signifies the magnitude of the impulse attributed solely to laser pressure, which can be approximated as:

$$\Delta \vec{V}_L = \Delta V_L \begin{bmatrix} \cos(\sigma)\cos(\alpha+\beta) \\ \cos(\sigma)\sin(\alpha+\beta) \end{bmatrix} \tag{6}$$

where the angles α and ϕ specify the direction of the periapsis and the position of the ground-based laser. The angle β specify the relative position of the target. The paramenter $\widehat{\rho}$, which can range between $-\pi/2$ and $\pi/2$ (Soldini and Scott, 2016). The impulse is calculated as $\Delta VL = \eta_c C_m \Phi \ \tau$, where η_c represents the efficiency factor, C_m $[P_a W^{^{-1}} m^{^{-2}}$ or $\frac{N}{W}]$ denotes the mechanical coupling coefficient, Φ stands for laser fluency, and τ refers to the area-to-mass ratio. Momentum transfer occurs when the pressure delivered to the target by the laser impacts its surface. This effect is made possible by pulsed laser ablation, characterized by the coefficient C_m (Phipps, 2014), assumed to be $C_m = \frac{p\tau}{\Phi}$, where Φ is laser fluency, p represents the ablation pressure imparted to the target by a laser pulse with intensity I over a given time and duration ($J/m^2 = I$).

In this study, we will consider values for laser ablation that are well-known for many materials and optical system parameters, along with typical numbers for the LODR system presented by (Phipps, 2011) and (Phipps, 2014):

The velocity variation vector of space debris due to the maneuver, ΔV, considering only the gravitational effect, is given by the difference between $\vec{V}_i$ and $\vec{V}_o$, where $\vec{V}_i = \vec{V}_\infty^- + \vec{V}_2$ and $\vec{V}_o = \vec{V}_\infty^+ + \vec{V}_2$. Here, the velocity of Earth with respect to an inertial frame is denoted as $\vec{V}_2 = (0, v_2, 0)$.

Thus total velocity variation of space debris during the close approach can be assumed to be

$$\Delta V = |\overrightarrow{V_0} - \overrightarrow{V_i}| + |\Delta \overrightarrow{V}_L| \tag{7}$$

Considering Eq.(7), it becomes possible to comprehend the velocity variation induced by the laser pulse applied to space debris through its spatial position. Consequently, the velocity vector resulting from laser pressure, combined with factors such as improper thrust direction and target shape, diminishes the efficiency of the laser pulse fluence in achieving the desired effect. With this understanding, the energy variation can be determined. It is given by Eq.(8), applied in the Broucke equation (Broucke, 1988):

$$\Delta E = E_o - E_i = \vec{V}_2 . \Delta \overrightarrow{V} \tag{8}$$

In this equation, E_i and E_o represent the specific orbital energies at the initial and final stages of the maneuver, respectively. Notably, a significant observation pertains to the energy loss encountered during close approaches to Earth, particularly when the laser impulse is applied near the space debris' anti-velocity direction. The study incorporates practical instances of collisions or captures, mirroring real mission scenarios.

After computing the variations in energy and angular momentum, the classification of orbits can be conducted based on specific criteria. These include elliptic direct orbits ($\Delta E < 0$), elliptic retrograde orbits ($\Delta E < 0$), hyperbolic direct orbits ($\Delta E > 0$), and hyperbolic retrograde orbits ($\Delta E > 0$). These conditions serve as fundamental guidelines for algorithmic development, especially when executing multiple Swing-Bys without corrections.

Equations (6) and (7), combined with (8), form the basis for calculating energy variations during these maneuvers. However, Eq. (8) alone is limited to identifying trajectories that remain within Earth's orbit, making it difficult to distinguish between capture and collision events. The inequality $V_+^2 \leq 2\mu_2/\rho_{deb}$ provides insights into scenarios where the space debris remains captured within Earth's orbit, which is crucial for assessing maneuver efficiency when utilizing laser pulses.

In scenarios devoid of laser pressure impulses, energy variation is solely dictated by gravitational effects, resembling a pure gravity Swing-By maneuver (Prado, 1996). According to this theory, noteworthy characteristics of the maneuver encompass $0^0 < \alpha < 180^0$, with maximum energy loss transpiring at $\alpha = 90^o$. Conversely, within the range $180^0 < \alpha < 360^0$, a maximum energy gain manifests at $\alpha = 270^o$, signifying energy acquisition propelled by gravitational forces during close approaches occurring behind Earth. Additionally, (Prado, 1996) observe that in a pure gravity Swing-By maneuver, the impact of close approaches on energy variation is negligible for $\alpha = 0^o$, $\alpha = 180^o$, and $\alpha = 360^o$.

The study primarily focuses on the initial phase of the maneuver, marked by the application of a single pulse to the space debris under predetermined initial conditions. During this phase, the motion of the debris is primarily governed by the gravitational fields of the Sun and Earth, in addition to the influence of laser pressure.

The orientation of the ground-based laser vector is hypothesized to be dictated by its deviation from the velocity vector of the space debris, with the angle α playing a pivotal role as a defining parameter.

4. Results and discussions

4.1. Considerations and parameters. Based on the equations presented (Equations 5-8), an analytical model was developed to conduct numerical simulations. A hypothetical scenario was considered, where a planar-shaped space debris moves in a Heliosynchronous orbit and undergoes a close approach to Earth. During this close approach, a resulting ΔV is applied, incorporating gravitational effects and the laser pulse.

The key parameters utilized to calculate the velocity variation induced on the debris surface by the laser pulse during close approaches to Earth at altitudes ranging from 100 to 1000 km. According to Phipps (2014), the parameters used become evident that beyond 1000 km, the effect of laser fluence diminishes, necessitating the use of large mirrors to counteract the diffraction spreading of light. Nevertheless, this study duly takes this aspect into account. To streamline the discussion, we introduce an efficiency factor η_c to accommodate the combined impacts of improper thrust direction and target shape in achieving the desired velocity change for direct incidence (Phipps, 2014).

Initially, all simulations were configured with a semi-major axis of $a = 9.97397 \times 10^7$, an eccentricity of $e = 0.4999$, and an inclination of $i = 0^o$. Subsequently, adjustments were made to encompass different initial velocities of the debris (V_p), altitudes ranging from 100 km to 1000 km (where laser fluence applies), $\phi = 0^o$ (representing the planar case), $\gamma = 0°$, and variations in the approach angle or position of the debris (α). Various configurations for the angles defining the incidence of the laser on the planar region of the debris were explored.

Understanding the significance of the angle α is crucial for assessing the practicality of a mission. A negative value for α implies that the direction of the laser pulse is opposite to the Earth-to-debris direction, resembling an attractor laser beam. Such a scenario is deemed impractical for mission purposes. Conversely, for symmetrical angles, the pulse intensity remains consistent with cases where $\alpha > 0^o$.

Furthermore, when $\tau = 0$ in Eq. (6), indicating a target area mass density of m^2/kg, the impulse becomes zero, and the energy variation is solely influenced by gravitational effects, rendering it a pure Swing-By maneuver (SB).

For small debris, where the specific size and mass of each target are unspecified, reducing the perigee of the debris ($\alpha = 0^o$) can be achieved not only by pushing antiparallel to its velocity vector but also by pushing radially outwards.

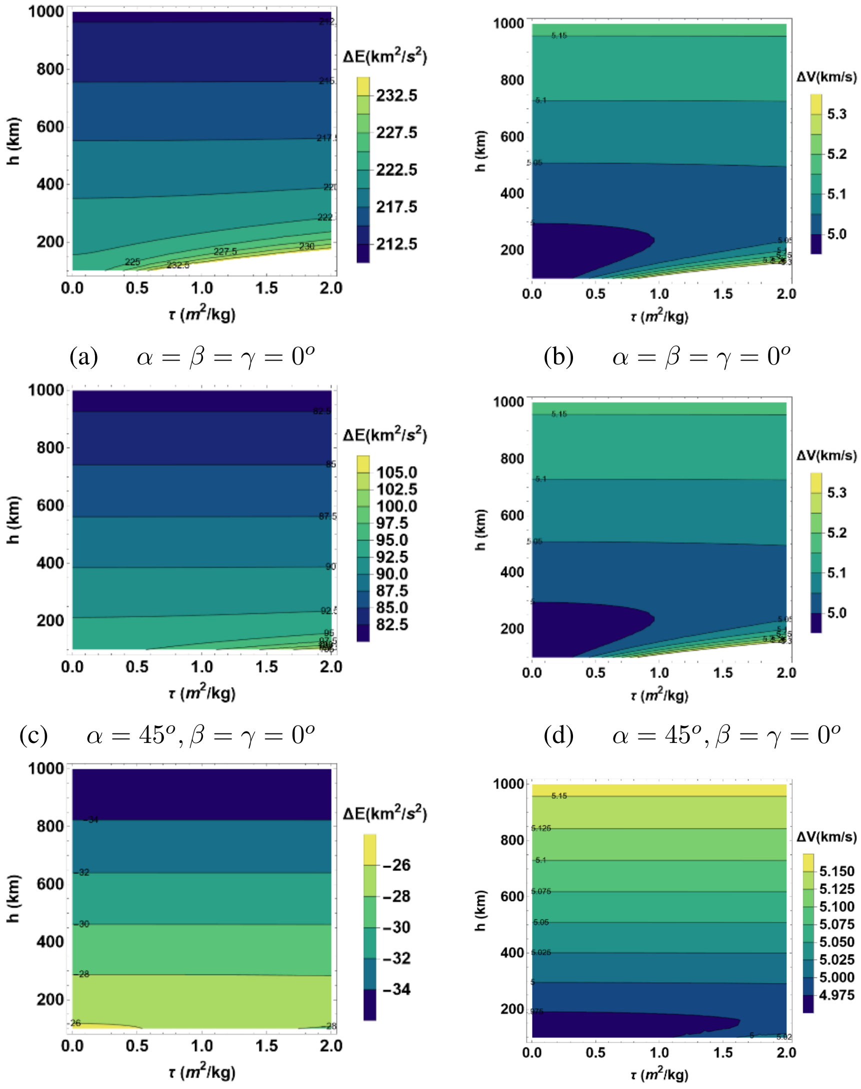
The assessment of the maneuver combined with the laser pulse was conducted in three distinct phases to comprehensively understand its implications. Initially, we examined the energy variation when the laser pulse maintains its efficiency, with $\beta = 0^o$. Following this, we investigated various deviations in β, shedding light on the energy variation when the laser doesn't hit the debris face perpendicularly. Subsequently, we delved into the changes in semi-major axis and eccentricity post-maneuver for specific conditions encountered in the simulations. Lastly, we scrutinized certain orbital characteristics where it's possible to mitigate the energy variation after the maneuver. This outcome is crucial when aiming to reduce the energy of space debris for re-entry.

For more precise calculations of laser-ablation-induced orbit change, refer to Phipps (2011). A simplified formulation is adopted here, eliminating the need to specify the actual size and mass of each target. Furthermore, for the combined effects of improper thrust direction, target shape, and target tumbling. A comprehensive discussion of debris shape factors and their impacts on coupling is provided in Schimitz *et al*. (2015).

4.2. Energy and velocity variation. In these analyses, the influence of τ and the altitude of the space debris becomes apparent when considering the laser orbital debris removal (LODR) perpendicular to the contact plane. Notably, by varying only the angle α (close approach), a significant energy variation was observed, particularly when the maneuver was executed near the perigee of the orbit (see Fig.2 (a)). Regarding ΔV (second column), minor numerical differences were noted, although only changing the position of the shaded areas, indicating the possibility of achieving the same impulse with varying characteristics (see Fig. 2(a)-2(c)).

A specific instance demonstrating an energy loss is presented in Figure 3(e). This finding reveals that the energy after the maneuver exceeded the energy before maneuvers, suggesting a potential for capturing this debris. Notably, according to its definition, $\alpha = 90^o$ induces the most substantial energy loss.

When combining the three angles presented in Figure 3, the results indicate that maneuvers with $\alpha = 10^o$ (Figures 3(a)-3(c)) and $\alpha = 40^o$ (Figures 3(d)-3(i)) exhibit relatively consistent energy variations. It's possible to see that the energy intensity remains consistent across different attitude variable combinations. In other words, with the same τ of the debris, similar energy variations can be achieved at different angles. These results are significant as they allow for the combination of conditions for various altitudes. The low variation observed is attributed to the low initial velocity before the maneuver.



(a) $\alpha = \beta = \gamma = 0^o$ (b) $\alpha = \beta = \gamma = 0^o$

(c) $\alpha = 45^o, \beta = \gamma = 0^o$ (d) $\alpha = 45^o, \beta = \gamma = 0^o$

(e) $\alpha = 90^o, \beta = \gamma = 0^o$ (f) $\alpha = 90^o, \beta = \gamma = 0^o$

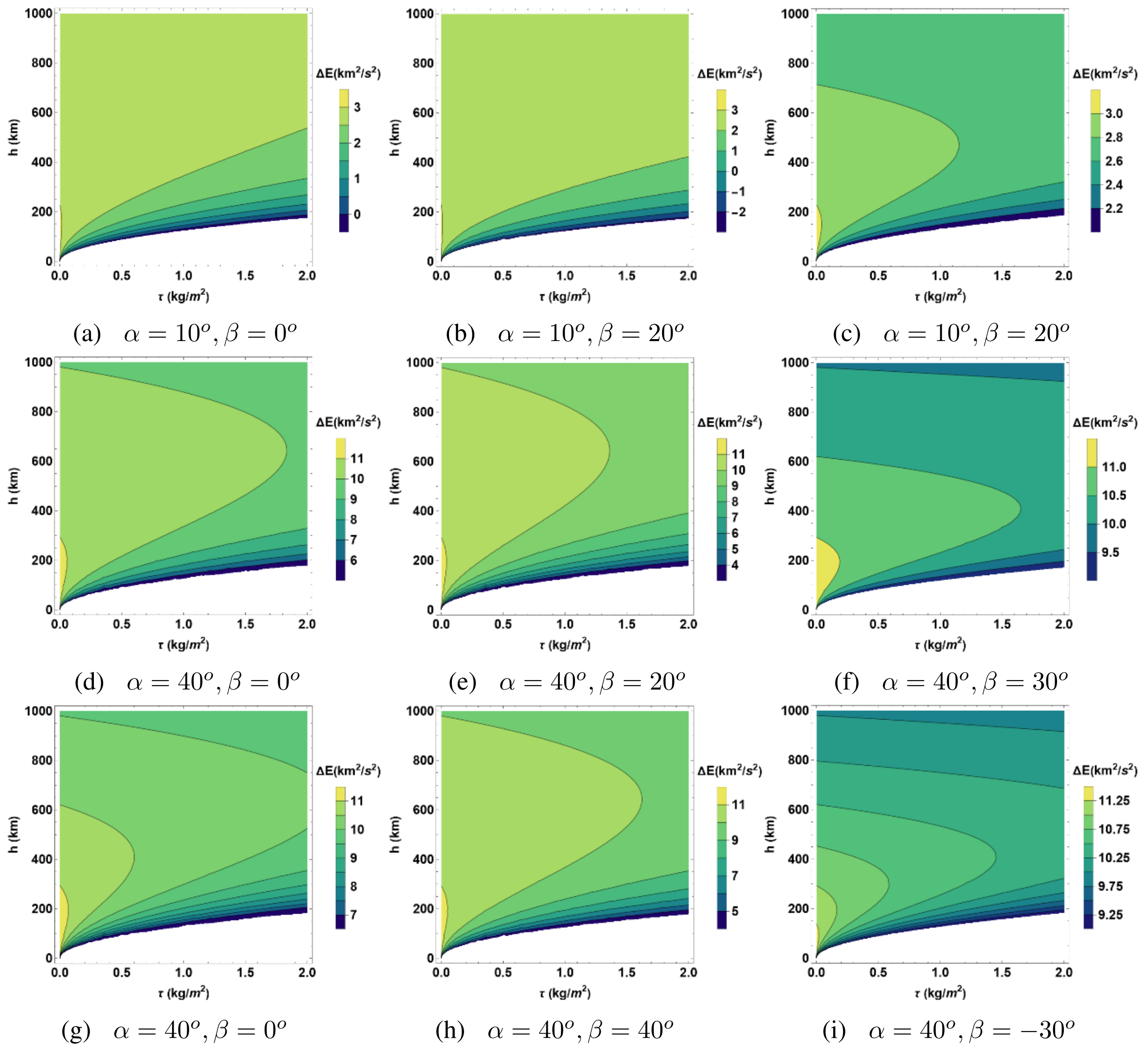
Fig. 2. Variation of Energy (first column) and Velocity (second column) of Space Debris Combined Maneuver with Laser Pulse, Considering Vp=10 km/s; $\gamma = \phi = 0$.

the studied cases, the most significant variations occurred above 200 km altitude, particularly as τ gradually increased. Figures 3(a)-3(b) represent the only instances where the energy after the maneuver was lower than the initial energy. This occurred due to the proximity to the perigee, combined with altitude and the size of the area-to-mass ratio.

Regarding the yellow region depicted in all figures (Figure 3), it is observed that smaller debris at altitudes between 100 km and 200 km experienced greater energy gains. This phenomenon is attributed to the higher laser fluence, and consequently, greater impulse in these conditions.

These cases occur due to the variation of τ and β combined with the variation of α. These conditions are important when we are interested in reducing the velocity of space debris. In this case, the α angle has little effect on reducing the intensity of the pulse during the passage of the debris. The greatest effect occurs when the distance of the debris to the Earth is taken into account.

4.3. Assessment of Re-entry Energy. The results depicted in Figures 4, 5, and 6 illustrate regions of potential re-entry for space debris following the maneuver, taking into account the effect of a ground-based laser. In these figures, regions where $\Delta E < 0$ are represented in gray, while regions where $\Delta E \geq 0$ are shown in white. These regions are determined based on the conditions outlined in Equation 7. shows severals results considering the position of the laser and two debris



(a) $\alpha = 10^o, \beta = 0^o$ (b) $\alpha = 10^o, \beta = 20^o$ (c) $\alpha = 10^o, \beta = 20^o$

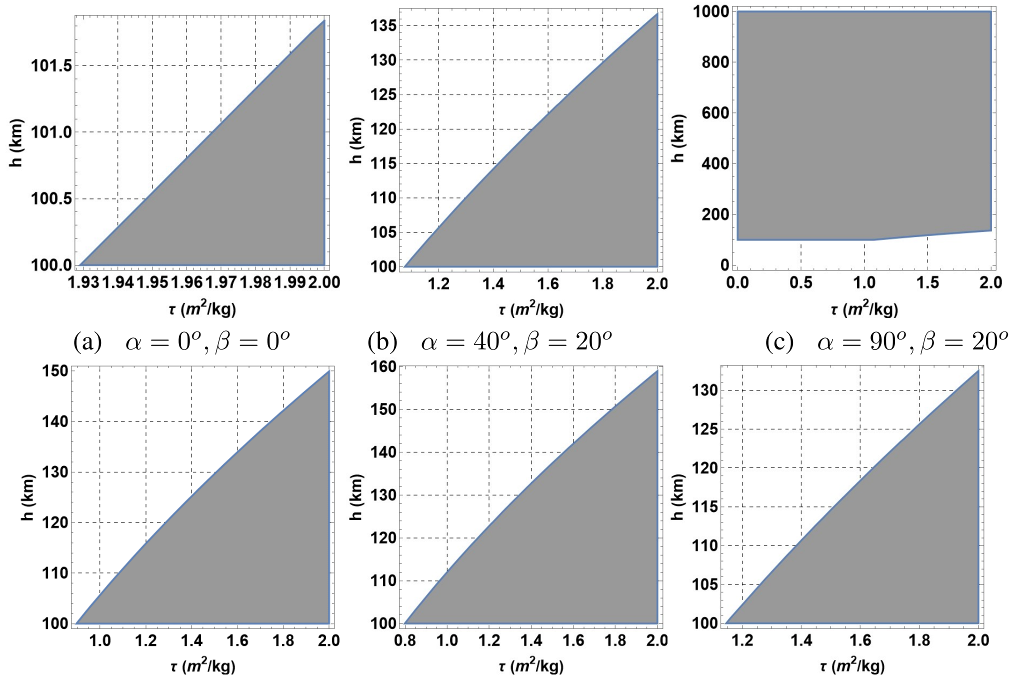
(d) $\alpha = 40^o, \beta = 0^o$ (e) $\alpha = 40^o, \beta = 20^o$ (f) $\alpha = 40^o, \beta = 30^o$

(g) $\alpha = 40^o, \beta = 0^o$ (h) $\alpha = 40^o, \beta = 40^o$ (i) $\alpha = 40^o, \beta = -30^o$

Fig. 3. Energy Variation of Space Debris After Combined Maneuver with Laser Pulse, Considering $Vp = 5$ km/s and Different Values of α and β.

attitude angles, resulting in $\Delta h \approx 60$ km. Particularly, Fig. 4(a) indicates a higher likelihood of capture due to the increased gravitational effect. It's worth noting that in Fig. 4(f), a slight modification in the inclination of the debris contact area limited the height to $h = 130$ km. Through the conducted simulations, it was observed that certain choices of the elements defining the target face incidence (β) of the laser led to a 38% increase in capture possibilities when considering the debris altitude during the maneuver.

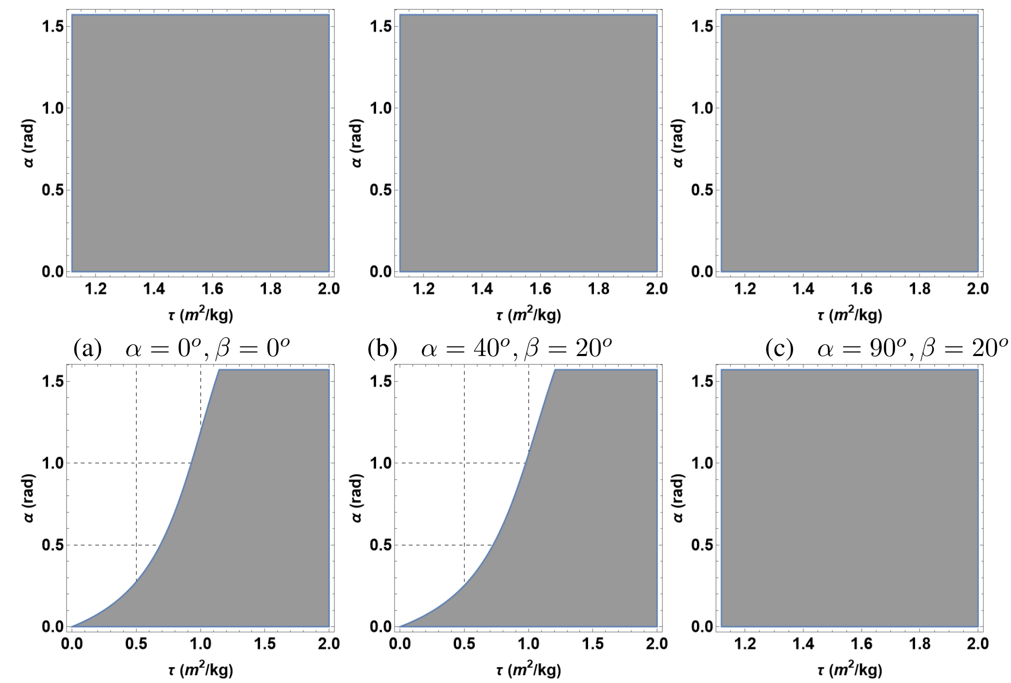
The defined re-entry region in this section elucidates the optimal angular position of the ground-based laser, along with the orientation of the debris during the laser-induced ΔV that yields negative energy post-maneuver. These findings are pivotal for evaluating the likelihood of re-entry or capture, predicated on the energy dissipation. Figure 6 was constructed based on the data presented in Figure 5 for a simulation where the debris was considered at a fixed position at $h = 1000$ km. The objective is to evaluate if there would be any region where it would be possible to capture the debris or if it would undergo reentry. It was observed that such characteristics were only obtained in maneuvers near the perigee and when there was not total incidence of the pulse considering the variation of the angles defining the attitude of the debris. The results presented in these Figures (5-6) aim to understand the influence of the velocity of space debris at two different altitudes ($h = 100$ km and $h = 1000$ km). In Figure 5(d), it is observed that even by modifying the velocity when the debris is at $h = 100$ km, it is possible to find conditions where the debris loses energy after the maneuver. Only in results 5(a)-5(e) was it possible to reduce the energy. In the remaining results, this combination to reduce energy after



(a) $\alpha = 0^o, \beta = 0^o$ (b) $\alpha = 40^o, \beta = 20^o$ (c) $\alpha = 90^o, \beta = 20^o$

(d) $\alpha = 40^o, \beta = 0^o$ (e) $\alpha = 40^o, \beta = 20^o$ (f) $\alpha = 40^o, \beta = 30^o$

Fig. 4. Energy Variation of Space Debris After Combined Maneuver with Laser Pulse, Considering $Vp = 5$ km/s and Different Values of α and β.



(a) $\alpha = 0^o, \beta = 0^o$ (b) $\alpha = 40^o, \beta = 20^o$ (c) $\alpha = 90^o, \beta = 20^o$

(d) $\alpha = 40^o, \beta = 0^o$ (e) $\alpha = 40^o, \beta = 20^o$ (f) $\alpha = 40^o, \beta = 30^o$

Fig. 5. Energy Variation of Space Debris After Combined Maneuver with Laser Pulse, Considering $Vp = 10$ km/s and Different Values of α and β.

the maneuver was only possible for debris with $\tau > 1$. When the results presented in Figure 5 were compared with Figure 6, it is observed that the gravitational effect was the main contributor to energy reduction after the maneuver, considering the increase in gravitational force at lower altitudes.

Finally, for debris close to $h = 100$ km, as presented in Figures 6(a)-6(c), it was not feasible to identify parameters conducive to re-entry across the three velocities considered. This is attributed to the altitude's heightened laser incidence and pronounced gravitational influence in comparison to other altitudes. Conversely, in the remaining results (Figures **??**-**??**), slight variations in debris attitude allowed for parameters facilitating reentry. It's imperative to underscore that the study does not definitively ascertain whether the debris will persist in capture or undergo reentry into the orbit; rather, it solely explores the potential occurrence of these outcomes.

4.4. General considerations. The discussion provided in this study offers valuable insights into the efficiency of the Swing-By maneuver, particularly when considering the application of laser impulses. While the traditional understanding suggests that the maneuver is most effective when the impulse is applied at periapsis, this study delves into the complexities surrounding the angle of approach (α) and its influence on maneuver efficiency. It's crucial to note that α is not a free parameter but is instead dependent on the entire trajectory of the debris around the Sun, limiting the feasibility of achieving specific angles. Thus, mapping the regions of maneuver efficiency becomes imperative, even if traditional Swing-By maneuvers without laser effects are primarily recommended for angles close to $\alpha = 270^o$.

From an astrodynamics perspective, the orbit modification induced by ground-based lasers emerges as a promising approach for space debris mitigation. The accessibility of ground-based lasers to a wide array of space debris objects underscores their potential significance. However, it's imperative to acknowledge the residual position uncertainty from laser tracking data, which must be factored into real-case simulations for orbit modification.

The results depicted shed light on the energy variations of debris after passing close to Earth, considering different scenarios with varying laser parameters. Notably, an increase in τ leads to additional energy gains due to the laser pulse, up to a certain threshold beyond which the effect becomes negligible. Moreover, the influence of α on energy variations is evident, particularly when the laser effect is considered.

The study highlights that the efficiency of the Swing-By maneuver, combined with laser impulses, is contingent upon various factors such as the gravitational parameter of Earth, approach angle, and velocity, as well as laser pressure. While the results demonstrate promising energy gains, they may not be sufficient for immediate escape or reentry maneuvers. Nevertheless, they provide valuable insights into optimizing laser-induced maneuvers for space debris mitigation, potentially reducing debris velocity for reentry or orbit alteration.

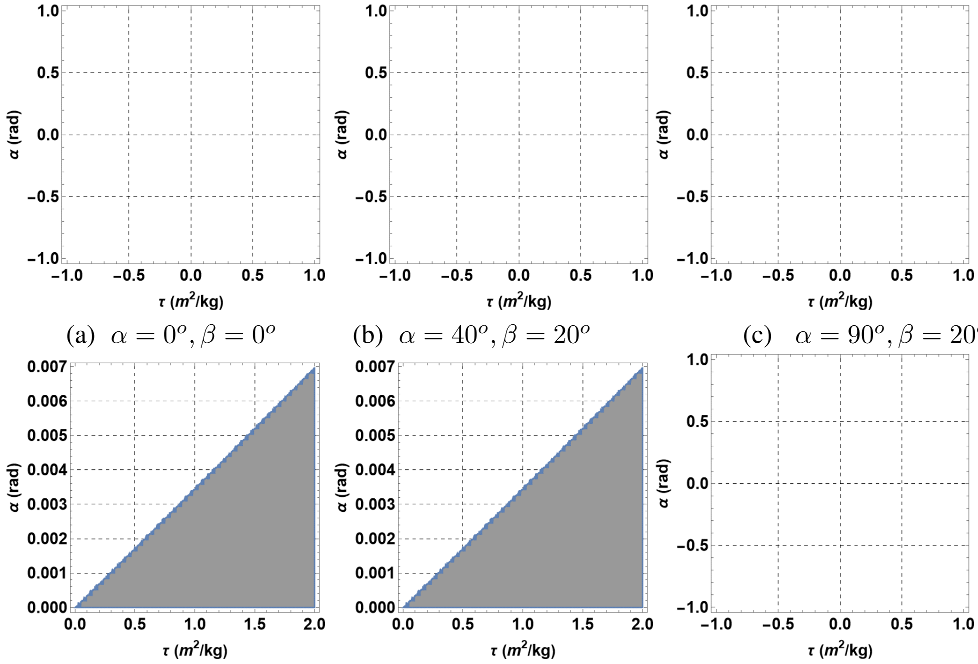
Furthermore, the findings contribute to understanding the post-maneuver orbital elements of debris, as determined by the relevant equations presented in the literature. Overall, this study enhances our comprehension of the interplay between Swing-By maneuvers and laser impulses, offering prospects for efficient debris mitigation strategies.

5. Conclusions

The study conducted herein provides valuable insights into the energy variations and velocity amplitudes resulting from close approaches with Earth, considering ground-based laser interactions. By deriving analytical equations to calculate energy variation due to laser pressure and close approach distance, the research elucidates the total energy variation for debris of different velocities and sizes.

While the study presents results considering single pulses, further investigations into multi-pulse scenarios are warranted to evaluate successful escape or reentry maneuvers. Notably, for small fragments with low τ values, maneuvering is primarily influenced by gravitational effects, whereas higher τ values yield significant velocity variations due to laser pulses.

The limitations imposed by the velocity of the debris under study and the Earth's gravity have led to relatively modest variations in velocity and energy compared to more massive celestial bodies, as reported in the literature. This outcome was anticipated due to the relatively weak gravitational effect of Earth during pure swing-by maneuvers. However, it is noteworthy that the angle of approach played a significant role in energy variation, particularly when combined with laser interactions during close approaches. Both energy gains and losses of approximately 30% were observed. Such variations are sufficient to remove debris from collision orbits or facilitate long-term reentry maneuvers. Considering variations in debris attitude and the angle of approach, energy variations were found to range from $3km^2/s^2$ to $11km^2/s^2$.This illustrates that debris attitude can significantly affect the feasibility of maneuvering or achieving reentry that enables gravitational capture of the debris. Additionally, the research underscores the importance of considering target orientation (β and γ) in simulations, as they impact the percent variation in maneuver efficiency. The search for ideal characteristics to achieve energy loss was explored in section 3.4. Most simulations indicated that regions of potential energy reduction were located near the perigee, particularly when variations in debris attitude contributed to a reduction in energy variation and, consequently, in the studied orbital elements. Moreover, the study demonstrates that



(a) $\alpha = 0^o, \beta = 0^o$ (b) $\alpha = 40^o, \beta = 20^o$ (c) $\alpha = 90^o, \beta = 20^o$

(d) $\alpha = 40^o, \beta = 0^o$ (e) $\alpha = 40^o, \beta = 20^o$ (f) $\alpha = 40^o, \beta = 30^o$

Fig. 6. Energy Variation of Space Debris After Combined Maneuver with Laser Pulse, Considering $Vp = 5$ km/s and Different Values of α and β.

method accuracy improves with decreased close approach distance and optimized ground-based laser positioning. This not only facilitates rapid calculations but also enables the identification of ideal initial conditions for maneuvering debris, aligned with mission objectives.

In conclusion, collaborative efforts should be pursued to leverage ground-laser-based applications as a methodology for space debris mitigation, thereby advancing implementation and ensuring its efficacy in addressing the evolving challenges posed by space debris accumulation. It is important to emphasize that this study was conducted in a hypothetical scenario and may require adaptation and refinement when applied to real-world cases, particularly regarding the consideration of single-pulse applications during maneuvers.

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