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Numerical Simulation of the Effects of Removing Small-scale Space Debris Using a Space-based Laser

Q. WEN[1,*], L-W. YANG[1], S-H. ZHAO[1], Y-W. FANG[1], Y. WANG[1] AND R. HOU[2]

[1]*Infomation and Navigation College, Air Force Engineering University, Xi'an 710077, Shaanxi Province, China*
[2]*Institute of China Electronic Equipment System Engineering Company, Beijing 100141, China*

This paper investigated the effects of space-based laser irradiating small scale space debris by numerical simulation. Laser ablation impulse coupling models were established by selecting typical materials of small scale space debris. The velocity variation of the space debris ablating by space-based laser was analysed, and the orbit manoeuvre of the small scale space debris irradiating by laser was modelled and investigated. The variations of the orbital parameters of the space debris orbit under the irradiation of high-power pulsed laser were simulated and analysed, and the effects of the spinning angular velocity and impulse coupling coefficient of debris and the power density and repetition of laser on debris removal efficiency were analysed and discussed. The simulation results show that, the assumed space-based laser can complete the mission of removing debris successfully by irradiating in one pass and the effects of the debris removal using space-based laser was described, which validated the feasibility of space-based laser debris removal and provided the necessary theoretical basis for the application of space debris removal by using space-based laser.

Keywords: *Space-based laser, space debris, numerical model, impulse coupling, orbit modification*

1 INTRODUCTION

A great deal of space debris has been produced from frequent space activities since human beings come into space age in 1957, which has seriously

*Corresponding author: Tel: +86 (0)177 9206 1747; E-mail: wenquan2411@163.com

polluted the space environment. The increasing number of space debris poses a considerable danger to orbiting satellites, humans in space and further space exploration activities. Space debris is mainly distributed in range from 400.0 to 2000.0 km of low Earth orbit (LEO), where the small scale space debris with 1 to 10 cm size can be neither monitored and tracked, nor shielded from orbiting spacecraft, posing a significant hazard for its large kinetic energy [1–3]. Hence, small scale space debris is considered as the most dangerous debris. It is urgent to remove small scale space debris in LEO actively to guarantee space environment security [4–6]. At present, the proposed solutions of space debris active removal mainly include chasing and grappling the objects, deploying nets to capture objects, attaching an electrodynamics tether and pulsed laser orbiting debris removal [7–9]. Pulsed laser orbiting debris removal has advantages such as simple operation, short response time, low cost, repeated use, and capable of both monitor and track activities. Therefore, it is considered as the most promising approach and it is the current research focus [10, 11].

Over the past few years laser debris removal is subject to a majority of studies all over the world. Besides, plenty of research projects on laser removal of space debris have been proposed, such as the ORION project of the USA [12] and the CLEANSPACE project of the EU [4]. Phipps *et al.* [13] proposed the approach of using a high power pulsed laser system on the Earth to remove debris, suggesting that laser orbital debris removal is the most cost-effective way to mitigate the debris problem. Schall [14] performed a discussion on the feasibility and basic principle for cleaning space debris in LEO by laser irradiation. Jin *et al.* [15] have researched laser removal method of elliptic orbital debris, indicating that the high power pulsed laser is a feasible method to remove debris. Shen [16] proposed a project of a space-based laser system, and the simulation results shown the space-based laser system can successfully protect the space station from the collision of debris. Recently, Phipps [17] presented a completely new proposal of a space borne ultraviolet laser system for space debris clearing and gave an estimated cost of removal. The previous researches are mainly in ground-based laser debris removal, in which relevant research institutions have made some progress.

The operating space of the ground-based laser is very limited due to its geographical location and distance. With the development of laser technology, the space-based laser debris removal has become a new solution to space debris removal for it can capture and monitor debris more conveniently and flexibly and hardly be affected by atmospheric. At present, researches on laser debris removal concentrate on the ground-based laser debris removal and involved less in the space-based laser debris removal. The action mechanism of space-based laser debris removal still lacks of further research at present; hence, it is necessary to study the basic principle and feasibility of space-based laser debris removal.

In this paper we discuss the variations of the perigee altitude of the small scale space debris orbit under the irradiation of high-power pulsed laser by simulating the comprehensive elimination process. In addition, the effects of space-based laser with different laser parameters irradiating debris with different physical parameters are concentrated on by numerical simulations.

2 EXPOSITION OF THE ELIMINATION PROCESS

As shown in Figure 1, space-based laser station is arranged in outer space, assuming that space debris runs counter-clockwise in an elliptical orbit and space-based laser station runs in a circular orbit which does not have to perform any orbital transfer with a constant radii, r_L. Besides, there is manoeuvre required for a proper orientation of laser action on the debris. We assume that 200.0 km is the maximum of the space-based laser operating range in consequence of constraint on volume power consumption of space-based laser [18].

When the range between debris and space-based laser (operating range) is below 200.0 km and the angle between debris velocity and laser irradiation

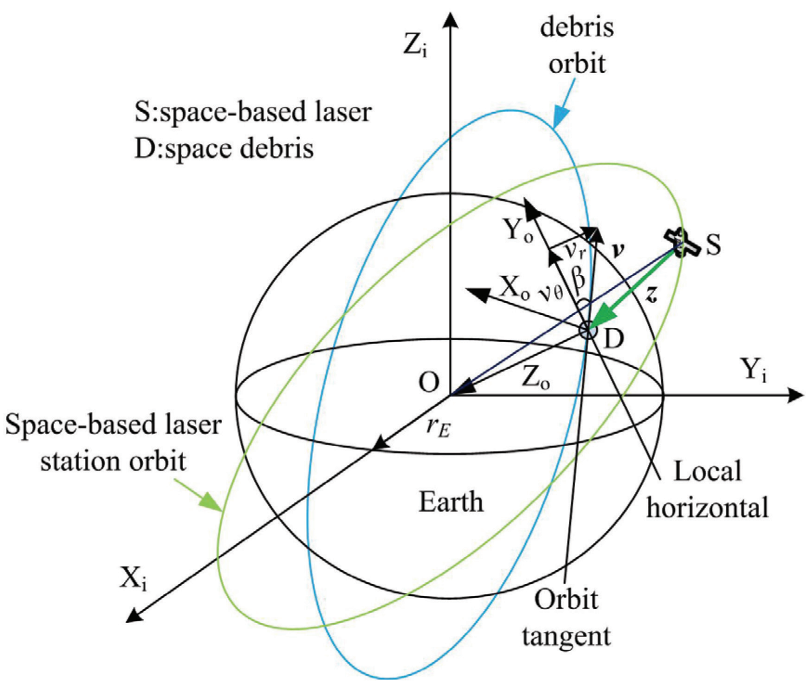

FIGURE 1
Schematic diagram of the removal scheme for orbiting space debris by using a space-based laser.

velocity increment (irradiation angle) is over 90.0°, which means debris runs into the elimination window of the space-based laser station, pulsed laser starts to irradiate debris. Afterwards, space debris obtains a velocity increment instantaneously, making debris orbit modified and the perigee decline [19]. When the debris runs over the elimination window, space-based laser stops working. The laser goes on to irradiate when debris runs into the next elimination window. It is considered as successful removal that debris is burned down owing to the aerodynamic heating effects [19].

3 MODEL DESCRIPTIONS

3.1 Laser ablation impulse coupling model

There is space debris of all kinds of irregular shapes in space on the basis of the National Aeronautics and Space Administration (NASA) research. The plate is the simplest example of an object, which can give expression of an off-beam response to laser ablation. Therefore, we select a plate to analyse.

Assumptions of the laser ablation impulse coupling model are made as follows:

(i) As is shown in Figure 2, the laser irradiates from the left hand side, which is parallel with x-component. The angle θ describes the orientation relative to edge-on;

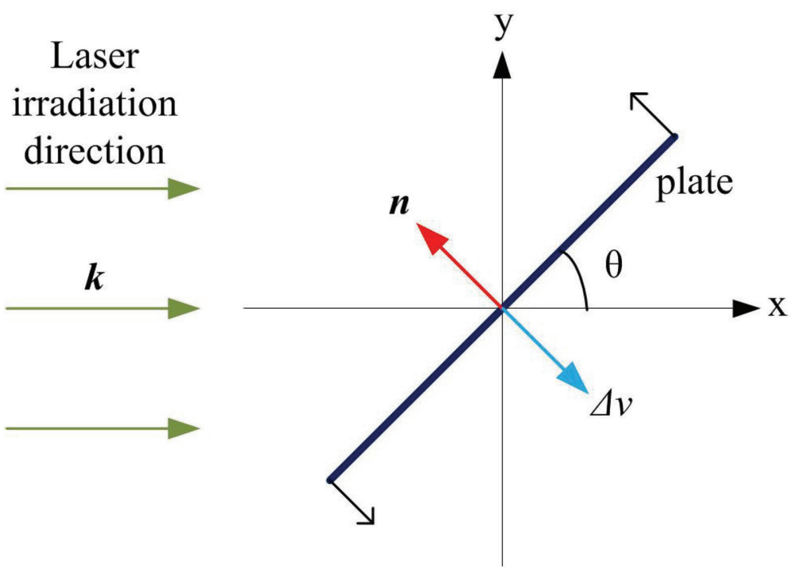

FIGURE 2
Schematic diagram of a thin plate projected onto the x-y-plane.

(ii) The Al plate is perfectly flat and thin in one dimension and spinning around an axis perpendicular to a surface normal going through the barycentre of the plate counter-clockwise;
(iii) The laser-target interaction only acts on *x*-*y* plane; and
(iv) The influence of *z*-component and the edge of the plate can be neglected.

We can now analyse the laser ablation impulse coupling model in detail. Assuming the plate is spinning at a random angular velocity $\boldsymbol{\omega}$ ($\boldsymbol{\omega} = \omega \boldsymbol{n}$) that is not affected by laser ablation, the surface normal, $\boldsymbol{n}$, of plate is described as

$$\boldsymbol{n} = \begin{pmatrix} -\sin(\omega t + \theta) \\ \cos(\omega t + \theta) \end{pmatrix} \tag{1}$$

We obtain the impulse of the target irradiated by high power pulsed laser, which can be described by [20]

$$m\Delta v = C_m E \tag{2}$$

where m is the mass of target, Δv is the velocity increment, E is the total on-target laser energy. If we recast Equation (2) as a force equation [21] then we get

$$m\frac{d\boldsymbol{v}}{dt} = -C_m \frac{dE}{dt}\boldsymbol{n} = C_m I \boldsymbol{k} \cdot \boldsymbol{H} \tag{3}$$

where $\boldsymbol{k}$ is a unidirectional laser beam with propagation unit vector, I is incident laser power intensity, $\boldsymbol{H}$ is the dyadic-form area matrix. The attained velocity increment under laser-target interaction in *x*-component and *y*-component are given severally by

$$\begin{cases} \Delta v_x = \dfrac{C_m IS}{2m\omega}\left[\omega t - \sin\omega t \cos(\omega t + 2\theta)\right] \\ \Delta v_y = -\dfrac{C_m IS}{2m\omega}\sin\omega t \sin(\omega t + 2\theta) \end{cases} \tag{4}$$

where S is the area of the plate.

3.2 Momentum transfer model of the space debris orbit

When the space debris moves into the elimination window of the space-based laser station, the high power laser starts to irradiate debris. Now, the true anomaly of debris is f_0. Taking advantage of corresponding dynamics equations we can easily get orbit radii of the debris, r_0, expressed as

$$r_0 = \frac{r_{p0}\left(1+e_0\right)}{1+e_0 \cos f_0} \tag{5}$$

where r_{p0} is the perigee radii before orbit transfer, e_0 is eccentricity before orbit transfer. The tangential and radial velocity components and the local orbital inclination are obtained, respectively, from

$$\begin{cases} v_{\theta 0} = \sqrt{MG/q}_{\,0}\left(1+e_0 \cos f_0\right) \\ v_{r0} = \sqrt{MG/q_0}\left(e_0 \cos f_0\right) \\ \beta_0 = \arctan\left(v_{r0}/v_{\theta 0}\right) \end{cases} \tag{6}$$

where M is the Earth's mass, G is gravitational constant, q_0 is semi-latus rectum before orbit transfer.

The total velocity of debris is given by

$$v_0{}^2 = v_{r0}^2 + v_{\theta 0}^2 = MG\left(\frac{2}{r_0} + \frac{1}{a_0}\right) \tag{7}$$

where a_0 is semi-major axis before orbit transfer. It is in Figure 3 that the geometrical variables for analysing laser orbit transfer are given.

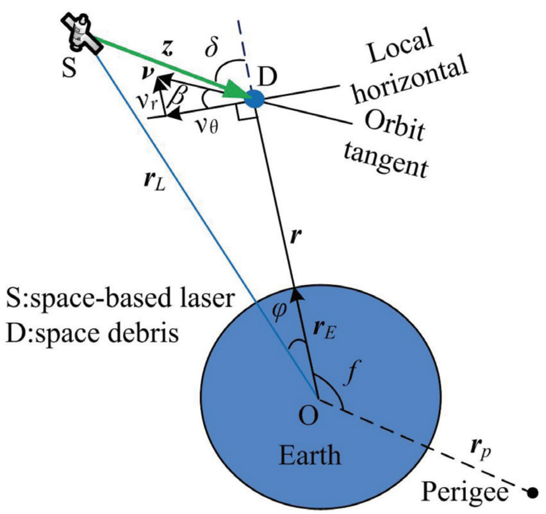

FIGURE 3
Geometry of the laser-target interaction. D is the space debris, S is the space-based laser station, δ is the direction of laser action on debris, r_L is the orbit radii of space-based laser station in the motion plane, r_E is the radii of the Earth, ϕ is the angle between orbit radii of space-based laser station and debris orbit radii, z is the range of space-based laser station and space debris.

As space debris is irradiated by the laser beam, a velocity increment is obtained and the original orbit of the debris is changed, as a result, the parameters of the orbit changed. The tangential and radial velocity increment components of space-based are described, respectively, as

$$\begin{cases} \Delta v_\theta = -\Delta v_x \sin\xi - \Delta v_y \cos\xi \\ \Delta v_r = -\Delta v_x \cos\xi + \Delta v_y \sin\xi \end{cases} \tag{8}$$

where ξ=β-δ. The orbital elements are given by

$$\begin{cases} \Delta a = \dfrac{2}{n_0\sqrt{1-e_0^2}}\left[\Delta v_r e_0 \sin f_0 + \Delta v_\theta \left(1+e_0\cos f_0\right)\right] \\ \Delta e = \dfrac{\sqrt{1-e_0^2}}{n_0 a_0}\left[\Delta v_r \sin f_0 + \Delta v_\theta \left(\cos E_0 + \cos f_0\right)\right] \\ \Delta\Omega = \dfrac{r_0 \sin\left(\omega_0 + f_0\right)}{n_0 a_0^2 \sqrt{1-e_0^2}\,\sin i_0}\Delta v_n \\ \Delta i = \dfrac{r_0 \cos\left(\omega_0 + f_0\right)}{n_0 a_0^2 \sqrt{1-e_0^2}}\Delta v_n \\ \Delta\omega = \dfrac{\sqrt{1-e_0^2}}{n_0 a_0}\left[-\Delta v_r \cos f_0 + \Delta v_\theta \dfrac{2+e_0\cos f_0}{1+e_0\cos f_0}\sin f_0\right] - \cos i_0 \Delta\Omega \\ \Delta M = n_0 - \dfrac{1-e_0^2}{n_0 a_0 e_0}\left[\Delta v_r\left(\dfrac{2e_0 r_0}{p_0} - \cos f_0\right) + \Delta v_\theta\left(1+\dfrac{r_0}{p_0}\right)\sin f_0\right] \end{cases} \tag{9}$$

From Equation (9), the change of the perigee and apogee orbit radii can be expressed as

$$\begin{cases} \Delta r_p = \left(1-e_0\right)\Delta a - a_0 \Delta e \\ \Delta r_a = \left(1+e_0\right)\Delta a + a_0 \Delta e \end{cases} \tag{10}$$

After a single pulsed laser irradiation, the perigee radii, r_{p1}, is r_{p0}+Δr_p and the true anomaly of debris changes into

$$f_1 = \arccos\left(\frac{q_1/r_1 - 1}{e_1}\right) \tag{11}$$

The rotation of main axis is f_1-f_0. We take advantage of Kepler's equation describing the relationship between time and location of debris to calculate the true anomaly, f_2, of debris after pulse interval. When next pulsed laser irradiates debris, repeat the analysis of irradiating effects of the next pulsed laser until debris is burned down owing to the aerodynamic heating effects.

4 SIMULATION RESULTS

Carbon is one of the most typical materials of space debris, which is chose to set up laser ablation impulse coupling model in this article. Space debris is mainly distributed in LEO, reaching the peak around the altitude of 800.0 to 1000.0 km [22]. We therefore take an example of the orbit altitude of 800.0 km to build corresponding momentum transfer models of space debris orbit. We assume that parameters of the apace-based laser and the typical material of small scale space debris are shown in Table 1 and Table 2. Since the change of debris' mass is very small during laser irradiation, we take no account of its effects on the orbit transfer to simplify the calculation. Assuming that the

TABLE 1
Laser performance characteristics.

Parameter	Value
Laser wavelength (μm)	1.06
Pulse width (nm)	100
Beam quality factor	2.0
Efficiency factor (%)	30
Laser spot radius (cm)	31
Laser pulse energy (kJ)	1
Power density (W/cm^2)	10^9
Laser repetition rate (Hz)	30

TABLE 2
Properties of the orbital elements.

Orbital Elements	Space Debris	Space-based Laser Station
Semi-major axis (km)	7167.5	7168.5
Eccentricity	1e-7	0
RAAN (°)	0.0	0.0
True anomaly (°)	0.1	0.0
Argument of perigee (°)	0.0	0.0
Inclination (°)	51.6	60.0

mass and the areal mass density of the debris are 0.75 kg and 10 kg/m^2, respectively, the initial orientation relative to edge-on is 30.0^o and the impulse coupling coefficient is 40 μNs/J. By means of the simulation of the comprehensive elimination process, the variations of the parameters of the typical space debris orbit under the irradiation of high-power pulsed laser can be obtained.

Figure 4 shows the relationship between the perigee altitude, apogee altitude and semi-major axis of space debris and the pulse number of laser

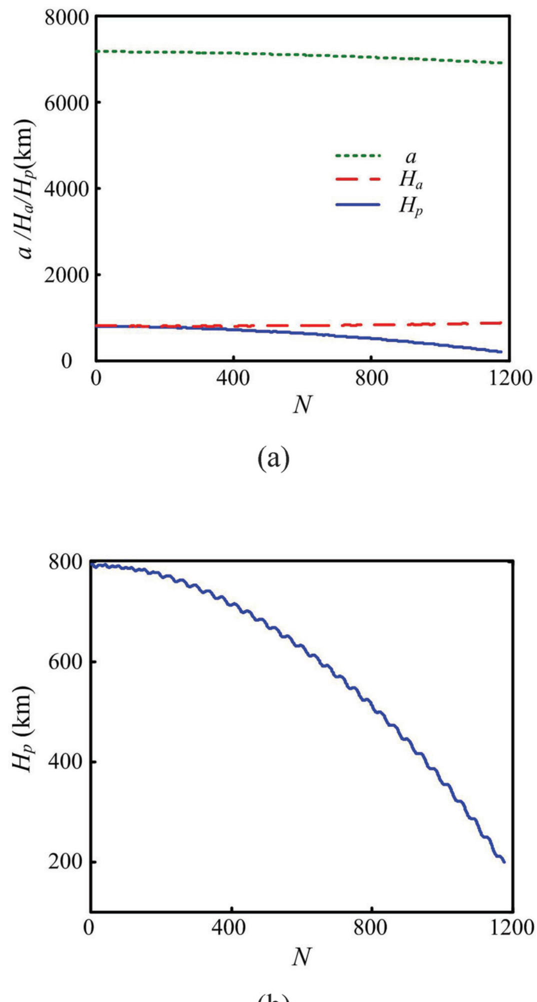

FIGURE 4
Graphs showing the relationship between (a) perigee altitude and the number of laser pulses and (b) perigee altitude/apogee altitude, H_a,/semi-major axis, a, and the number of laser pulses.

within the elimination window of space-based laser. As is shown in Figure 4, the perigee altitude and semi-major axis declines gradually and the apogee altitude goes up a little. The perigee altitude of carbon debris is fallen down below 200.0 km irradiated by 1176 pulses from space-based laser where the space debris can be burnt out to be captured as a result of the aerodynamic heating effects. What we can see is that the perigee altitude of carbon debris decreases and presents a cyclical change with the increase of pulse number of laser. Since the interaction duration of a single pulsed laser is just a couple of nanoseconds, we consider the space debris in a 'frozen state'. As a result, we assume space debris obtains a velocity increment instantaneously irradiated by a single pulsed laser. At the same time, the orbit transfer and space debris rotation are not considered during the interaction of the single pulsed laser and space debris; however, when it refers to multi pulsed laser, the pulse interval cannot be neglected. During the pulse interval, the spinning debris is rotated with some degrees. Thanks to the off-beam response to laser ablation, the impulses the high power laser impacts on the space debris change with the spinning of debris, resulting in a cyclical change of the perigee altitude partial view to it. The simulation results are what might be expected in the elimination process. From what has been discussed above, the typical space debris in typical altitude of 800.0 km can be removed successfully through 1176 pulses of laser in total by using the assumed space-based laser.

To simplify the analysis we assume that the space-based laser is coplanar to the debris orbit following. In order to discuss the effects of different materials of debris on de-orbiting, two typical materials of small scale space debris (aluminium whose impulse coupling coefficient is 14 μNs/J and carbon) as examples are chosen. As is shown in Figure 5, the curves of the perigee

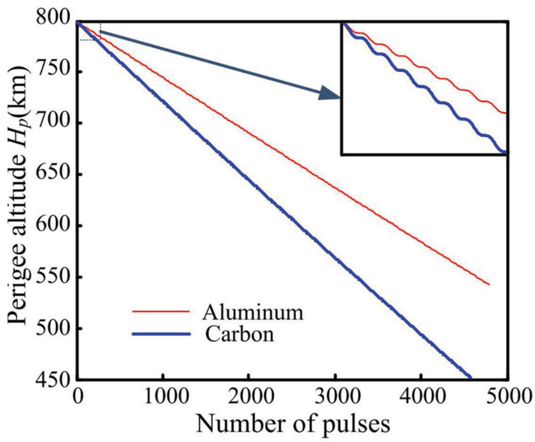

FIGURE 5
Perigee altitude of two typical materials of debris *versus* the number of laser pulses.

altitude of two typical materials of debris and the pulse number of laser is given. From this figure, as the pulse number of laser increases, the perigee altitudes of both typical materials of debris present a cyclical change and neither are fallen down below 200.0 km within one pass. The perigee altitude of aluminium debris is fallen down to 543.0 km irradiated by 4785 pulses of the space-based laser, while that of carbon debris is fallen down to 451.9 km irradiated by 4577 pulses. Moreover, what we can see is that the perigee altitude of carbon debris declines more obviously than that of aluminium debris irradiated by the same laser. The impulse coupling coefficient of the laser-target interaction is a parameter that links target impulse with laser energy directly and an important parameter index to evaluate the effects of laser debris removal. We can see that the impulse coupling coefficient of the laser-carbon interaction is greater than that of the laser-aluminium interaction (see the work of Phipps *et al.* [13] for further details). The figure shows that debris of lower impulse coupling coefficient is irradiated more pulses by the laser. The greater the impulse coupling coefficient is, the less time and energy is required for pulsed laser debris removal and the higher the removal efficiency is.

The following discusses the effects of spinning characteristics of space debris on debris orbit modification in elimination process in detail. Figure 6 gives a description of the relationship between the perigee altitude of carbon

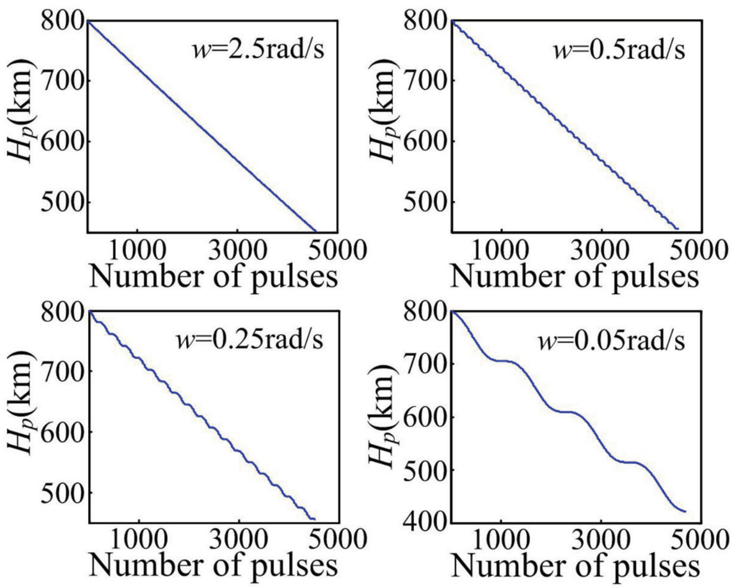

FIGURE 6
Perigee altitude of carbon debris with different spinning angular velocity *versus* the number of laser pulses.

debris with different spinning angular velocity, which is severally 2.50, 0.50, 0.25 and 0.05 rad/s, and the number of laser pulses within the elimination window of space-based laser. Figure 6 shows that the perigee altitude of debris with above four spinning angular velocity are fallen down to 451.9, 455.7, 455.9 and 421.9 km respectively irradiated by 4577, 4527, 4521 and 4695 laser pulses. The lower the spinning angular velocity is, the greater the amplitude of the cyclical change of the perigee altitude and the longer the period of that is; however, the spinning angular velocity affects the time and energy required for pulsed laser debris removal less when the velocity is relatively great. When it comes to relatively low spinning angular velocity, the removal efficiency is affected quite more thanks to its greater amplitude and longer period of the cyclical change of the perigee altitude.

From Figure 7, we can see the curves of the perigee altitude of carbon debris irradiated by lasers with different power density and the pulse number of laser. As shown in Figure 7, the perigee altitude of carbon debris irradiated by laser with different power density decreases with the increase of the pulse number of laser. Due to the spinning of debris, all of the perigee altitude changes periodically. Within the maximum operating range during the elimination process of the space-based laser with the power density of 10^9 W/cm^2, the perigee altitude of carbon debris can be fallen down below 200.0 km irradiated by 808 pulses in one pass, which means that the space debris is removed successfully. The perigee altitude of carbon debris is fallen down to 451.9 km irradiated 4577 pulses by the laser with the power density of 10^8 W/cm^2, while it is fallen down to 757.8 km irradiated 5399 pulses by the laser with the power density of 10^8 W/cm^2. The two lasers stop working for the debris is over the operating range of lasers. It is necessary for the

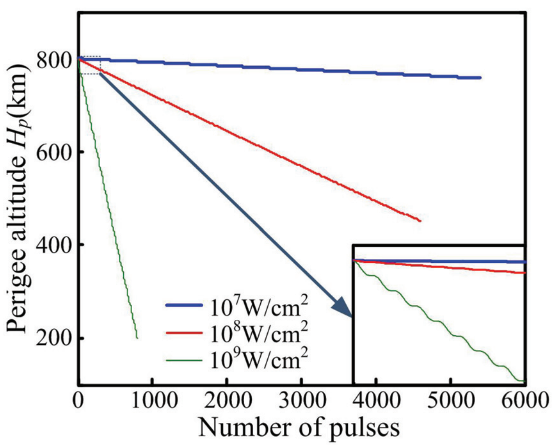

FIGURE 7
Graph showing the perigee altitude of C debris *versus* the number of laser pulses when irradiated by different laser power densities.

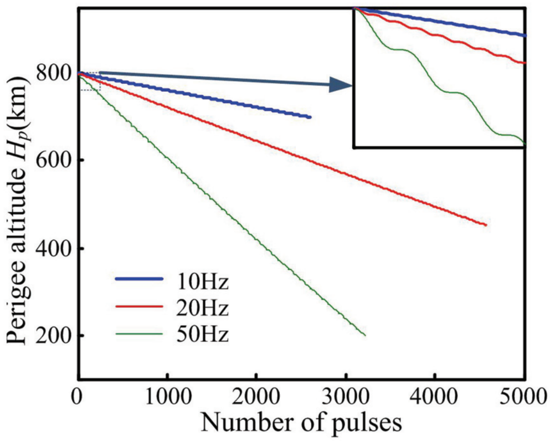

FIGURE 8
Graph showing perigee altitude of C debris *versus* the number of laser pulses when irradiated by different laser pulse repetition rates.

two lasers to irradiate debris in another pass when the debris runs into the elimination window until debris is burnt out to be removed. As we can see that the higher power density of laser can remove debris more effectively. Partial view to this figure, the amplitude and longer period of the cyclical change of the perigee altitude of carbon debris is greater irradiated by the laser with higher power density.

Through simulation of the relationship between the perigee altitude of carbon debris irradiated by lasers with different repetition rate and the pulse number of laser, the discussion of the effects of lasers with different repetition rate is made. Figure 8 shows that the laser with repetition rate of 50 Hz can remove carbon debris successfully in one pass irradiated 3223 pulses. Neither of the lasers with repetition rate of 20 and 10 Hz can complete the removal mission in one pass. The similar conclusion is drawn as last figure that the debris is removed more effectively irradiated by laser with higher repetition rate. Additionally, the laser with higher repetition rate contributes to the greater amplitude and longer period of the cyclical change of perigee altitude.

5 CONCLUSIONS

In this paper we select typical materials of plate to serve as examples to build a momentum transfer model of space debris orbit irradiated by assumed space-based laser. The effects analysis of space-based laser irradiating small scale space debris by numerical simulations is described and conclusions are drawn as:

(i) The small scale space debris in typical altitude of 800.0 km can be removed through 1176 pulses of the laser by using the assumed space-based laser, verifying that the space-based laser is a feasible method of small scale space debris removal;
(ii) The less time and energy is required for pulsed laser debris removal and the removal efficiency is higher when the impulse coupling coefficient of the laser target interaction is greater;
(iii) The perigee altitude of debris decreases and presents a cyclical change with the increase of pulse number of laser. The cyclical change of the perigee altitude of debris with greater spinning angular velocity has greater amplitude and longer period. The removal efficiency is affected few by the spinning angular velocity when the velocity is relatively great; and
(iv) The lasers with higher power density and repetition rate remove debris more effectively. The cyclical change of the perigee altitude of carbon debris has greater amplitude and longer period irradiated by the laser with higher power density and repetition rate.

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NOMENCLATURE

e_0	Eccentricity before orbit transfer (km)
E	Laser energy (J)
f_0	True anomaly of the debris
G	Gravitational constant
$\boldsymbol{H}$	Dyadic-form area matrix
I	Laser power intensity (W/cm^2)
$\boldsymbol{k}$	Unidirectional laser beam with propagation unit vector
m	Mass (kg)
M	Earth's mass (kg)
$\boldsymbol{n}$	Surface normal
q_0	Semi-latus rectum before orbit transfer
r_0	Orbit radii of debris (km)
r_{p0}	Perigee radii (km)
S	Area of the plate (m^2)
v	Velocity (m/s)

Greek symbols

ω Angular velocity (rad/s)

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