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Cleaning space debris with a space-based laser system

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Abstract High-energy pulsed laser radiation may be the most feasible means to mitigate the threat of collision of a space station or other valuable space assets with orbital debris in the size range of 1–10 cm. Under laser irradiation, part of the debris material is ablated and provides an impulse to the debris particle. Proper direction of the impulse vector either deflects the object trajectory or forces the debris on a trajectory through the upper atmosphere, where it burns up. Most research concentrates on ground-based laser systems but pays little attention to space-based laser systems. There are drawbacks of a ground-based laser system in cleaning space debris. Therefore the placement of a laser system in space is proposed and investigated. Under assumed conditions, the elimination process of space debris is analyzed. Several factors such as laser repetition frequency, relative movement between the laser and debris, and inclination of debris particles which may exercise influence to the elimination effects are discussed. A project of a space-based laser system is proposed according to the numerical results of a computer study. The proposed laser system can eliminate debris of 1–10 cm and succeed in protecting a space station.

1. Introduction

Several organizations among the world's space-faring nations are concerned about the increasing risk of space debris interfering with operational satellites. Although no one knows when this will turn into a crisis, there is general consensus that sometime in the next one or two decades, the frequency of collision events in congested orbital regions will dramatically increase. The result will be a loss of access to an important part of space.[1–3] The debris size range of greatest potential danger and therefore interest is 1–10 cm according to results of international research. It is because on one hand debris smaller than 1 cm can be shielded to decrease damage to a spacecraft. On the other hand, there are few enough objects larger than 10 cm, so that it is generally possible to maneuver a spacecraft to avoid colliding with them.[4] Aimed at cleaning dangerous space debris, an idea was born in the United States, Germany, Australia, Russia, etc. in a succession to use the radiation of high-power lasers to annihilate dangerous particles up to several centimeters in diameter. Under laser irradiation, part of the debris material is ablated and provides an impulse to the debris particle. Proper direction of the impulse vector either deflects the object trajectory or forces the debris on a

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trajectory through the upper atmosphere, where it burns up. Some space-faring nations such as America, Russia, the European Union have done research on space debris eliminated by laser. However, most research concentrates on ground-based laser systems[4–11] but pays little attention to space-based laser systems.

There are, however, drawbacks of a ground-based system: a rather long distance, 350–1000 km, must be bridged to focus a laser beam on a particle with a radius of only a few centimeters, and an extremely high steering accuracy must be met. In addition to a formidable target detection and acquisition system, a very large beam director mirror is needed to obtain a high enough laser fluence and power density on a target to produce a noticeable impulse. A large fraction of the laser beam power will be wasted because a transmitter telescope cannot produce a small enough focal spot at these long distances. Only continued processing of a debris particle over several orbital revolutions may be sufficient to lower the orbit substantially and allow the atmosphere eventually to do its cleaning work. Another opportunity to continue the processing on a certain particle exists only when it passes over the station again. Several stations around the globe may, therefore, be preferred, if the time for final elimination should be reduced. Cleary, the system can only be used in a preventive way and cannot counter an immediate collision threat.[12]

In this work, the placement of a laser system in space is proposed and investigated. This method gives much more flexibility to counter the debris problem. Several factors such as laser repetition frequency, relative movement between the laser and debris, and inclination of debris particles which may exercise influence to the elimination effects are discussed. A project of the space-based laser system is proposed to protect space stations according to the numerical results of computer study data.

2. Profile of the space-based laser system

Direct ablation mode and ablation back-jet mode are two modes in debris eliminated using a laser. The former mode is primarily aiming at tiny debris particles, and laser energy is used to burn down debris particles. The latter mode is pointed at larger debris particles, and laser energy is used to transfer orbit of debris. Debris particles would be burned down by the drastic aerodynamic heating effect.

Ablation back-jet mode is used to clean debris of a centimeter magnitude. Laser energy would be transformed to thermal after the irradiation, and the laser spots would increase the temperature of the irradiation region to the melting or even boiling point of the debris material. The plasma produced by ablation would expand in a velocity much higher than that of sound when the temperature rises to the vaporization point. The debris particle would be exerted by a reaction force. The force would lead to object trajectory, as shown in Fig. 1. Perigee altitude of the debris is reduced after the reactions of multiple laser pulses, and the particle would be burned down by the aerodynamic heating effect.[13]

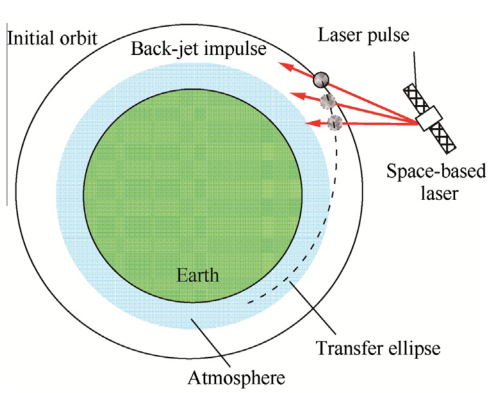

Fig. 1 Removal process of a debris particle.

A typical debris particle would reenter in a few days due to atmospheric drag if its perigee is less than 200 km. For the same debris at a 500-km perigee, the natural decay time is approximately 18 years.[1] Therefore, the 200-km altitude is defined as the threshold for successful removal.

2.1. Choice of laser beam transmission

A suitable laser should satisfy the following conditions: (1) high average power and peak power; (2) high pulse energy; (3) high laser beam quality; (4) mature technology and easy to maintain.

Possible candidates could be a solid-state laser operating in a burst mode (heat capacity laser, 1.06 μm). There is no mechanically driven component equipped in a solid-state laser and no need to refuel the system; therefore, it is particularly reliable.

The laser wavelength is λ, mirror diameter D_b, focal length z, Gaussian beam constant a', and N times diffraction limit. The diameter of the far field laser spot can be expressed as

$$d_s = a' \frac{N\lambda z}{D_b} \tag{1}$$

Assume that the laser wavelength is 1.06 μm and the pulse width is 7 ns. The focal spot should not be too small in consideration that it is difficult to track and aim a debris target. However, too large a spot causes serious energy waste and is difficult to reach the ablation threshold as well. Therefore, assume that the diameter of the far field laser spot is $d_s = 15$ cm. For a uniform plane light wave laser beam of diffraction limit $a' = 2.44$ and $N = \sqrt{2}$, maximum z is 100 km. The mirror diameter D_b can be calculated as

$$D_b = a' \frac{N\lambda z}{d_s} = 2.44 \text{ m} \tag{2}$$

Above all, the mirror diameter should be 2.44 m in order to get a 15-cm spot.

2.2. Mass model

For the changes of the motion parameters, the debris mass is the most relevant quantity, whereas the dimensions are important for the optical coverage of the debris body. Of course, the connection between these two quantities is determined by the geometry of the particle, which may be completely arbitrary.

For statistical purposes, a model has been employed. In this model, the mass is related to some power of the diameter ($m \propto d^{2.26}$). A graphical representation is given in Fig. 2, and compared with the relation for either a sphere ($m \propto d^3$) or a thin disk ($m \propto d^2$). According to this model, a 10-cm-diameter object would have a mass of 70 g if it is aluminum and 40 g if it is carbon.[12]