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Laser Radiation for Cleaning Space Debris from Lower Earth Orbits

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High-power laser radiation may be the most feasible means to mitigate the threat of collisions of a space station or other valuable space assets with orbital debris in the size range of 1–10 cm. The utilization of a laser in orbit is investigated. Use of the laser allows both the direct protection against an impact and the removal of all debris passing at some distance. Under laser irradiation, part of the debris material is ablated and provides an impulse to the debris fragment. Proper direction of the impulse vector either deflects the object trajectory (defense option) or forces the debris on a trajectory through the upper atmosphere, where it burns up (cleaning option). The limitations of the laser method for both options are illustrated by sample calculations for an averaged pulsed laser power of 100 kW and debris consisting of either aluminum or carbon. Under favorable geometrical conditions, debris masses of 100 g at a passing distance of up to 70 km can be removed, and debris on a collision flight path can be deflected by 500 m and more. An orbital debris removal system should be established and operated by an international society.

Nomenclature

c_m	=	coupling coefficient, Ns/J
d	=	debris diameter, cm
d_{flyby}	=	flyby distance, km
dv	=	velocity change by laser impulse, m/s or km/s
E	=	laser pulse energy, J
H	=	orbital altitude, km
M, m_0	=	initial debris mass, g
m_i	=	remaining debris mass after ith impulse, g
R_d	=	minimum debris trajectory distance, km
R_m	=	laser range, km
r	=	relative flight-path distance, R_d/R_m
s	=	debris flight distance during laser operation, km
u	=	transfer velocity, m/s or km/s
v	=	velocity, m/s or km/s
v'	=	closing velocity of debris, km/s
w	=	debris velocity after impulse, km/s
α	=	angle between debris velocity vectors in the two reference frames, deg
β	=	angular change of debris velocity vector, deg
Δm	=	ablated mass, g
Δv	=	effectively required velocity change, m/s or km/s
δ	=	inclination difference between debris and laser orbit, deg
θ	=	elevation angle, $\Delta H/R_m$
λ	=	laser wavelength, μm
μ	=	ablation rate, μg/J

Subscripts and Superscripts

A	=	apogee
bup	=	burnup
c	=	circular orbit
D	=	debris
e	=	exhaust, blowoff
f	=	final
P	=	perigee
S	=	station
$'$	=	station fixed coordinates

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Introduction

MAN-MADE orbital debris is mainly the result of purposefully destroyed satellites and of upper-stage explosions.[1,2] Although passive methods and agreements to avoid such events have been adapted by some spacefaring nations, the total number of operational and nonoperational space objects is still increasing with an annual rate of approximately 3% (Ref. 3) (Fig. 1). [At an altitude of 600 km, there is an increase at a rate of nearly 5% (Ref. 4).] About 10,000 larger bodies with diameters of more than 10 cm are continuously monitored so that their orbital data are well known, and dangerous encounters can be avoided. Objects with diameters in the range between 1 and 10 cm are difficult to find from Earth, cannot be observed continuously, and change their orbits rapidly due mainly to gravitational forces. Their number is unknown but exceeds those of the large bodies by at least an order of magnitude.[5] These fragments pose the main threat to space assets, in particular to the very large and long-living International Space Station (ISS). Because of the high relative speeds, any collision with such a particle is equivalent to a high-intensity explosion. There also exists a vast number of even smaller particles down to the size of dust, which may still be capable of puncturing the skin of a space suit or a pressurized tank. However, crewed modules can be shielded mechanically against particles of this size, and much like the overwhelming majority of natural meteoritic particles, they are not considered as a deadly danger.

Can laser radiation clean orbital debris from low Earth orbits (LEO)? With increasing concern about the growing number of debris, about a decade ago the idea was independently born in the United States[6,7] and Germany[8–10] to use the radiation of high-power lasers to annihilate dangerous particles up to several centimeters in diameter. Annihilation with laser radiation could be done as a means to shield a large and precious space asset from a direct collision, or in a preventive way, by eventually clearing all of this debris from LEO. The clearing procedure could be started from the orbit of such an asset and continued in a next step in all Earth orbits up to 2000-km altitude. The altitude range from 300 to 2000 km is where most satellites operate and also where most man-made debris is located. The process of annihilation with coherent high-energy radiation can be by complete vaporization,[7] ablation or fragmentation by thermal and thermomechanical processes, or by making use of the mechanical impulse that is induced on a body by blowing off material from it. The process of this latter case is equivalent to laser propulsion by mass ablation.[11] If the direction of the impulse is such that the

Table 1 Summary of the assumptions for the model calculations

Assumptions			Consequences	
Circular orbit at burnup altitude, km		$H_A = 500$ $H_P = 100$	Velocity increment	115 m/s
Laser				
Pulse energy		1 kJ/pulse		
Repetition rate		100 Hz	Average power	100 kW
Pulse length		100 ns		
Wavelength		1–2 μm		
Optics				
Aperture diameter		≤2.5 m	Focal diameter	10 cm
Range		100 km		
Debris				
Diameter		≤10 cm	Fluence	10 J/cm^2
Mass		≤100 g	Intensity	10^8 W/cm^2
Material	Al	C		Al C
Coupling coefficient	2×10^{-5}	1.38×10^{-5} Ns/J	Minimum mass fraction	
Ablation rate	80	12.5 μg/J	to ablate, %	37 10

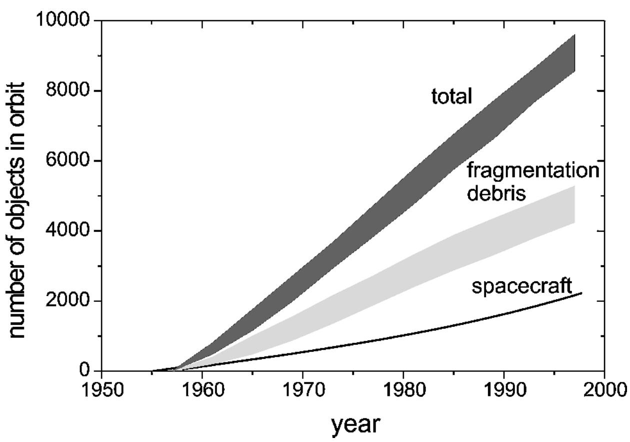

Fig. 1 Development of the number of objects in orbit over time.

orbital velocity is reduced, the object assumes an elliptic orbit with a lower perigee. If the perigee is low enough, the object will descend into the atmosphere, where friction will further reduce the orbital altitude until the particle burns up. If the created impulse is large enough, this happens after half a revolution around the Earth.

Over the years, the laser method has been proposed several times[12–14] and still seems to be the only feasible and economic way to tackle the problem of small debris. A few years ago, a detailed project study was undertaken by Phipps et al.[15] and Phipps,[16,17] who proposed a high-energy laser system called ORION. This system is based on a large, pulsed, frequency converted, solid-state laser, as is under development for the inertial confinement fusion in the United States (beamlet demonstration project at the Lawrence Livermore National Laboratory). The laser should preferentially be located on a high mountain to reduce the atmospheric attenuation of the laser beam. It would be supported by detection systems, as well as by an additional laser to probe the atmosphere and help to compensate the diffractive effect from turbulence on the high-power laser beam. Such a system is feasible in principle, and other types of pulsed lasers have been suggested as alternatives to the beamlet system. Phipps[17] has presented parameter charts for the selection of the most suitable and economic laser parameters for debris clearing with an Earth-bound laser, including cost estimates.

There are, however, drawbacks of an Earth-deployed system: The transmission through the atmosphere requires extensive installations to compensate for the inevitable atmospheric beam distortion. The optical problems in beam transmission through the atmosphere and the impact on the fluence that arrives at the target and on the residual debris lifetime has been discussed by Campbell and Taylor.[18] A rather long distance, 350–1000 km, must be bridged to focus the 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 the target to produce a noticeable impulse. A large fraction of the laser beam power will be wasted because the transmitter telescope cannot produce a small enough focal spot at these large distances. Only the continued processing of a debris particle over several orbital revolutions may be sufficient to lower the orbit substantially and to 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. Clearly, the system can only be used in a preventive way and cannot counter an immediate collision threat.

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, including the defense against a threatening collision with a debris object. The space-based system is small and can dispense with features that are necessary for an Earth-deployed system. Specifically, no means are required to compensate atmospherical effects. Furthermore, the laser range can be reduced by almost an order of magnitude. By the relying on the assumed availability of a certain laser, the specific situation for a space-based laser system will be outlined, and the possibilities, peculiarities, and its limitations will be discussed. Numerical results of a computer study for both deflection and elimination are presented and discussed with respect to the scaling of various parameters. Some deployment aspects of a space-based laser system are briefly discussed.

Assumptions

The problem encompasses a multitude of possible parameters. They begin with the given orbits and materials of the debris and end with the selectable properties of the laser and its beam delivery system. The latter determine the laser–matter interaction and the reaction of the debris. To simplify the description and for transparency, certain simplifying assumptions will be made for the modeling of the laser treatment of debris. Without restricting the generality of the conclusions, these concern 1) the orbits of laser and debris, 2) the characteristics of the laser and of the laser beam transmission, and 3) the size and material of the debris and its interaction with high-power laser radiation. The assumptions are summarized in Table 1. Results gained using these assumptions may serve as a baseline from which scaling or interpolation to other conditions is mostly straightforward.

Orbits

Although substantial amounts of debris are located at altitudes up to 2000 km, with a maximum at 800 km, the calculations in this work will be restricted to the interaction range of a laser placed at an altitude of 500 km. Higher orbits are more demanding in terms of required energy to remove a particle, yet pose no fundamental limitation. In fact, the ISS is positioned below this altitude (approximately at 400 km). The number density of the debris is also lower

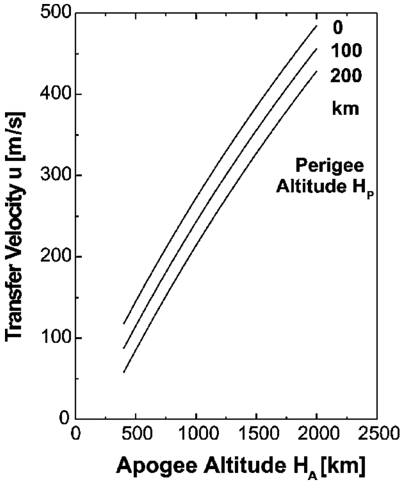

Fig. 2a Required transfer velocity from circular orbits at the altitude H_A into an elliptic orbit with perigee altitude H_P.

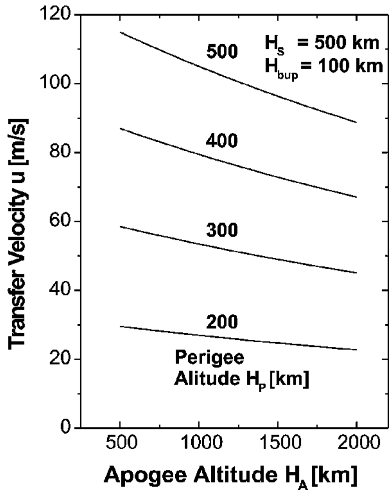

Fig. 2b Required transfer velocities at $H_S = 500$ km altitude for elliptic orbits into a new ellipse with perigee altitude for burnup $H_{\mathrm{bup}} = 100$ km.

there, with a likewise reduction in demands. Practically, it is most reasonable to deploy a first laser system on or in the vicinity of the space station. Later an autonomous, freely roaming antidebris laser satellite may be deployed in space for clearing debris at higher orbital bands.

For simplicity, the debris and the laser station are assumed to move on circular orbits and, thus, in the same orbital plane. In reality, elliptical debris orbits with a small eccentricity are more likely and may cross the station orbit under an angle of up to ±3 deg out of the orbital plane. However, this eccentricity will not change the numbers substantially and is rather a problem for the detection system.

The transfer velocity is the difference between the debris velocity in the original orbit and the apogee velocity of an ellipse with a lower perigee height H_P. It is a measure for the orbital energy that the debris must lose. As a worst-case scenario, we intend here to remove a debris object at once. Thus, a transfer into an ellipse with $H_P = 100$ km is assumed, resulting in an assured burnup in the atmosphere after half a revolution. This rather stringent assumption is by no means imperative. When a certain number of revolutions before burnup occurs is allowed, either a higher perigee becomes possible with a subsequently lower transfer velocity or the processing of larger and/or heavier debris objects becomes possible. For the assumed ellipse, the transfer velocity at 500 km is $u = 115$ m/s. If the laser is placed in a higher orbit to deal with debris circling near the outer edge of the cloud, higher transfer velocities would be needed. Figure 2a shows the required velocities as a function of the laser orbit height and the burnup perigee. Debris on elliptical orbits with the perigee below 500 km requires a smaller transfer velocity than debris on a circular orbit, as seen in Fig. 2b. Here u is taken as the difference of the velocities at the altitude of 500 km for debris with a fixed apogee but different perigees.

Laser

A suitable laser will produce a pulse energy of 1 kJ at a repetition rate of 100 Hz and with a pulse length of 100 ns. This amounts to an average laser power of 100 kW. Such lasers do exist already or can be scaled up immediately from existing devices with a minor adaptation in the pulse length. These lasers operate on the wavelength of either the CO_2 or CO molecule at 10.6 μm or around 5 μm (Refs. 19 and 20). For smaller emitter optics and better coupling characteristics to most materials, a preferred wavelength would be rather in the range of 1–2 μm.

Possible candidates could be the ArXe laser with a wavelength of 1.7 μm (Ref. 20), a solid-state laser operating in a burst mode (heat capacity laser, 1.06 μm) (Ref. 21), or even a pulsed chemical oxygen–iodine laser (1.315 μm) (Ref. 22). The ArXe laser is an e-beam sustained electric discharge laser, just like the cited CO_2 or CO laser, and operates with a closed-flow loop. Only leaking or permanently chemically reacted gas has to be replaced eventually in these lasers. The lifetime of a properly cooled e-beam foil, the most critical element in this type of laser, can extend 10^7 shots before it has to be replaced. Nonlinear optical methods are currently investigated to produce near diffraction limited laser beams.[23,24] A heat capacity laser of the assumed power level has not yet been demonstrated, but presently seems conceivable. After the emission of a pulse sequence, the laser needs a certain cooling time, and it may be unable to counter a double incidence. On the other hand, a solid-state laser may not require mechanically driven parts or refueling and is, thus, particularly reliable. Finally, the oxygen–iodine laser is operating on gas and liquids and derives its power from a chemical reaction, which consumes fuel. From the specific energy of the laser of about 100 J/g of laser fuel, it can be estimated that about 10 ton of fuel have to be provided to remove 100 kg of orbital debris. This mass corresponds to the amount of debris in the considered size range within a shell of 100 km thickness and requires on the order of 1 GJ of laser energy for removal.

The power of 100 kW is selected for simplified scaling only, and smaller lasers may suffice. Continuous-wave lasers are also not principally excluded. In this case, an intensity $>10^5$ W/cm^2 would be preferable at the target. This, however, demands quite large laser powers. Shorter wavelengths and shorter pulse durations could improve the ablation process and the mechanical impulse to the target.[25] However, low laser efficiencies of existing short-wavelength lasers ($\lambda < 1$ μm) would drive up size and costs for such installations.

Laser Beam Transmission

Let the maximum range of the laser beam be defined as that for which the beam can just be focused down to the size of the largest debris for a realistic handling by the laser method, namely, 10 cm in diameter. If this range were 100 km, a director mirror of 2.5 m in diameter (similar to the Hubble telescope) would be needed to project a near diffraction limited, 1–2-μm-wavelength laser beam onto a 10-cm target. For the assumed pulse energy and length, the fluence at the target is then 10 J/cm^2 and the intensity 10^8 W/cm^2. If the target is smaller than the focal diameter of the transmitted laser beam, energy is wasted. On the other hand, with a variable focal length a higher fluence is possible on a smaller target if the target is closer. Reducing the laser pulse energy, but maintaining the same energetic conditions on the target, implies a reduction of the focal spot and, thus, a proportional reduction in range if the mirror diameter is kept constant.

Debris Material

Aluminum and carbon are selected as typical materials of the debris. Also most laser–material interaction data are available for them. The mechanical impulse that is exerted if some material is ablated can be related to the incident laser pulse energy with the aid of the impulse coupling coefficient $m\Delta v = c_m E$. A coupling coefficient $c_m = 2 \times 10^{-5}$ Ns/J (= 2 dyne s/J) for Al and 1.4×10^{-5} Ns/J for C is assumed consistent, with the spread of typically found experimental values and the laser characteristics specified earlier.[25–27] The coupling coefficient could be higher by a factor up to five by proper matching of the laser parameters such as intensity, wavelength, and pulse length to the debris material.[25] In the light of this freedom, the assumed c_m values can be considered as rather conservative. A compilation of scaling laws for the estimation of the laser–material interaction parameters, in particular, the coupling coefficient, has been presented by Hammerling and Remo.[28] It is more difficult to find total ablation rates μ for various materials in the literature. Total ablation rates are the sum of directly vaporized and ionized material, as well as of fragmentized pieces from thermal stress in brittle materials or from the expulsion of liquid by the pressure pulse. In fact, if no precise material ablation is required, as is the case in industrial laser materials processing, expulsed liquid may make up the largest part in the ablation process.[29] Expulsion of liquid occurs in particular for Al and for laser pulses with pulse lengths from tens of nanoseconds up to microseconds. Knowledge of the ablation rate is important for repetitive pulse operation because, for a fixed coupling coefficient c_m, the achievable velocity increases with reducing mass. For the ith laser pulse, the velocity increase is $\Delta v_i = c_m \cdot E/m_i$ with

$$m_i = m_0 - \sum_i \mu E$$

where m_0 is the initial mass and E the laser pulse energy. In accordance with Kuznetsov and Varygin[13] and with Lenk et al.,[26] a total ablation rate $\mu = 80 \times 10^{-9}$ kg/J = 80 μg/J is assumed for Al. A lower ablation rate delays the achievement of the final transfer velocity. For this reason, alternative calculations have been performed for carbon as the target material, using $c_m = 1.38 \times 10^{-5}$ Ns/J and $\mu = 12.5$ μg/J from Lenk et al.[26] The hypothetical limit is $\mu = 0$, which is equivalent to a single pulse operation, where mass change is unimportant.

From the momentum equation $m\Delta v = \Delta m_e v_e = c_m E$ and using $\Delta m_e = \mu E$, the blowoff velocity can be expressed as $v_e = c_m/\mu$, yielding a value of 250 m/s for Al and 1100 m/s for C. Although the number for Al might seem rather low, note that it is an effective value and includes the expulsion of liquid in the form of droplets. We remark that, although favorable in reducing the debris mass for little energy expenditure, the expulsion of liquid in the form of droplets adds to the total number of debris. However, these droplets are very small (micrometer size[29]), distribute rapidly, and pose no serious danger. The process of liquid expulsion from meltable materials can be significantly enhanced if a double-pulse mode is applied. A second laser pulse of very short duration (picoseconds range) and comparatively low energy can create a megabar pressure pulse on the liquid surface and drive out the melt sideways.

Knowledge of the blowoff velocity v_e allows the estimation of the minimum mass Δm that has to be ablated and, from this, the minimum laser energy for achieving the required velocity for atmospheric entry, that is, $u = 115$ m/s. Applying the fundamental rocket equation in the form

$$\Delta m/m_0 = 1 - \exp(-u/v_e) \tag{1}$$

results in a minimum mass fraction of 37% for Al and 10% for C under ideal conditions. As will be explained later in detail, orbital geometry will dictate higher ablation fractions.

It is implicitly assumed here that the thrust vector lies in the direction of the laser beam. Irradiation of a skew flat plate will blow off ablated material normal to its plane and, therefore, experience a different thrust direction. However, for tumbling fragments and irregularly ablating surfaces, the average thrust vector over several pulses will point in the direction of the laser beam emitter. A directional efficiency factor between two-thirds and one may be used for the achieved dv_i if such a situation is to be considered.

Mass Models

For the change of the motion parameters, debris mass is the more 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, suggested by Eichler and Rex,[30] 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. 3 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-diam object would have a mass of 70 g if it were Al and 40 g if it were carbon.

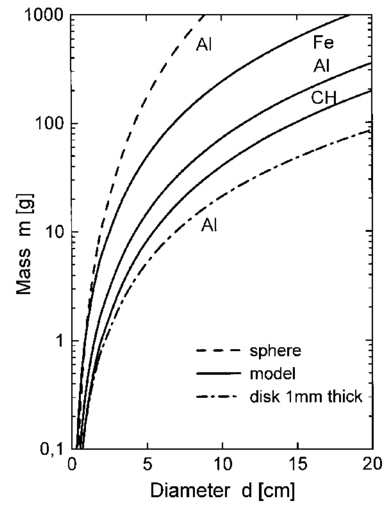

Fig. 3 Mass vs diameter for different shapes and materials.

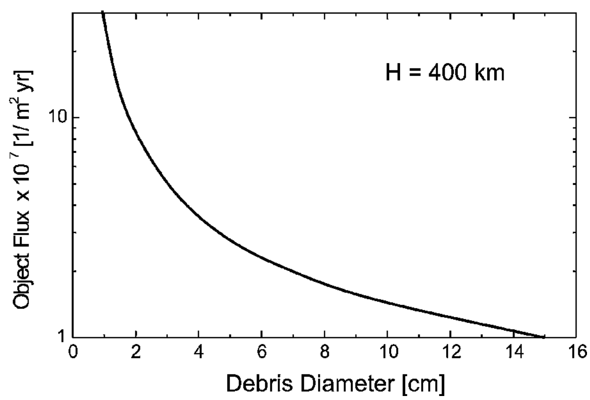

Fig. 4 Object flux vs debris diameter.

Debris Environment

The number of debris particles per cubic kilometer is a function of the altitude and the inclination of the orbit. It can readily be assumed that the distribution of the smaller debris with altitude and orbital inclination corresponds closely to the distribution of the large, trackable bodies, in particular at higher altitudes, and hence, it is known. Unknown, however, is the number density, which is required to estimate clearing times and total energy. Estimates for the total number of small debris vary by large factors, depending where the limits are set, but 100,000 is taken as a reasonable average. Figure 4 displays the object flux in the orbit of the ISS as a function of the diameter according to the current assumptions.[5]

The angle δ between the orbital inclination of the laser station and of the debris at the encounter defines the closing velocity v'. This relationship is visualized in the two vector diagrams of Fig. 5, which show the velocity of the station, v_S, and of the debris, v_D, in an inertial frame. Because of the assumption of circular orbits at the same altitude, both are equal in magnitude, namely, being the circular velocity v_c for that altitude. The debris is approaching the station with the relative velocity v', which is the vectorial difference between the velocities v_S and v_D. The closing velocity is important in calculating the available irradiation time and the flight trajectory. From the distribution of the debris cloud over various inclinations,[30] one can calculate velocity spectra of the debris as shown, for example, in Fig. 6 for a low and for a high inclination of the station. We note that in the first example with $\delta = 28.5$ deg, the bulk of debris has a closing velocity between 4.5 and 13.7 km/s, the most frequent velocity being 11.2 km/s and the mean velocity 9.5 km/s. Although

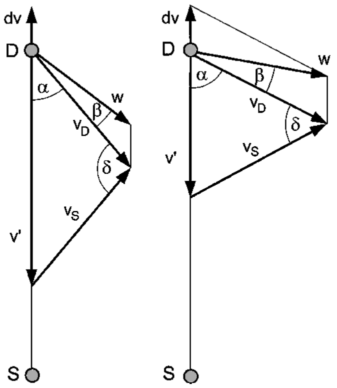

Fig. 5 Definition of the closing velocity v' and its change with the inclination angle δ.

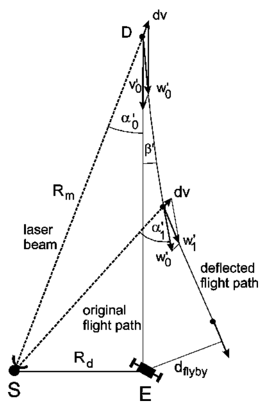

Fig. 7 Effect of laser action on the debris flight path.

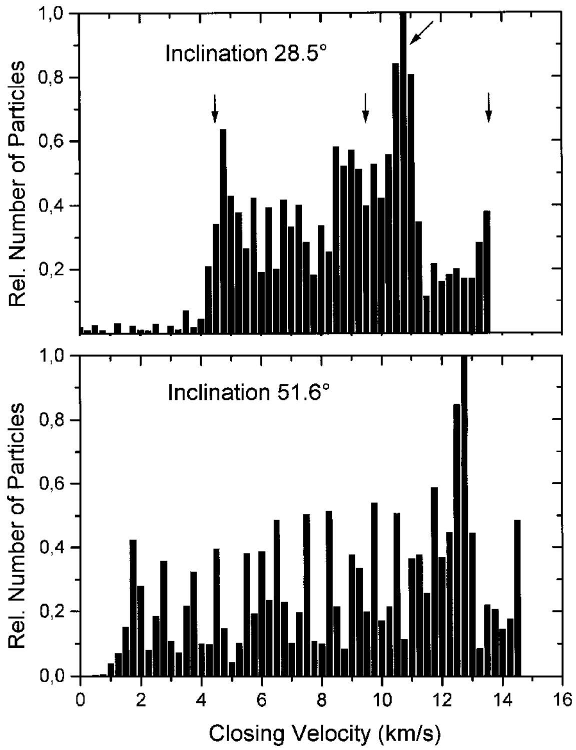

Fig. 6 Relative particle numbers for different closing velocities and inclinations at an altitude of 500 km.

being an arbitrary selection to some extent, these four velocities will serve as exemplifying parameters in the section on the calculations. The second example, with $\delta = 51.6$ deg, holds for the ISS. A prominent peak appears here at 12.5 km/s. Hence, results for this velocity class will lie approximately halfway between those for 11.2 and 13.7 km/s and are not worked out explicitly. The latter spectrum extends almost homogeneously to velocities as low as about 1.5 km/s.

Geometrical Situation in Orbit

Collision Trajectory

Figure 7 analyzes the general geometrical situation during a near encounter between a laser station S and a debris particle D in their common plane and in a coordinate system that moves with the station S (primed notation). A laser beam directed from S toward the particle D with closing velocity v' would induce a decelerating velocity increment $\mathrm{d}v$ on D according to the created impulse. The particle D, therefore, changes its velocity in magnitude and direction to $w' = v' + \mathrm{d}v$. In the special case that D is actually going to hit S at the encounter point E (the marked distance R_d is zero), the exertion of an impulse by the laser generally cannot prevent the collision. The velocity v' is then only altered in magnitude and not in direction, because no side component of the impulsive force acts on the debris. In fact, before the debris would lose all of its closing velocity and stop in front of the station, it would be vaporized completely, provided that there is sufficient laser power and interaction time available; or, if the encounter could be delayed long enough, the debris on its enforced descent trajectory might dive deep enough to pass underneath S.

It must be accepted that in many cases a laser cannot defend a station against a direct collision as long as it is deployed on the station itself, except by being able to destroy the target fully. However, a full destruction is possible in many cases: The highest closing velocity in the presented scenario with some probability is 13.7 km/s. Beginning the laser interaction with the debris at a distance of 100 km would allow a maximum irradiation time of 7.3 s until impact, corresponding to the vaporization of 58 g of aluminum or 9 g of carbon. According to the mass model, this corresponds to a 9-cm-diam Al or a 5-cm C object. Therefore, debris smaller than this, in principle, can be annihilated. As shown in Fig. 4, the great majority of the debris is indeed smaller.

A way out of the restriction to smaller debris is to place the laser aside of the asset that is to be protected.[8,14] In this case, the impulse imparted on the debris has a side component, which leads to a deflection of the trajectory away from its original destination by the flyby distance d_{flyby} (Fig. 7). This deflection effect will be larger, the farther away the laser is located from the encounter point E ($R_d > 0$). Of course, the offset, R_d, must be much smaller than the laser range R_m. Alternatively, the laser source may still be placed onboard the station, but the laser beam is redirected by a relay mirror at some distance from the station. In the real application, the laser or, in particular, the relay mirror will coorbit with the station on the same trajectory, either ahead or behind of it. Any other orbit would otherwise imply a continuous relative motion between the two bodies.

Near Encounter

The immediate collision threat is a rare occasion in comparison to a near encounter or close flyby within the range of the laser. Therefore, the available laser should always be used to eliminate every closely passing debris. In the case of a near flyby, the geometrical situation is the same as in the earlier example with a displaced laser or mirror as shown in Fig. 7. The only difference is that now E is the point of closest approach and is set off from the space asset located at point S. The opportunity to eliminate a particle depends on various geometrical parameters, such as the maximum laser range R_m, the flyby distance R_d, and the laser beam angle α. The laser beam angle is the angle enclosed between the laser beam and the flight path of the debris and changes during the operation as indicated in Fig. 7 (indices 0 and 1 mark two situations during laser operation).

The required transfer velocity is reached if $u = |v_c| - |w_f|$ with $|v_c|$ denoting the scalar value of the original circular vector velocity and $|w_f|$ denoting the scalar value of the final velocity that leads to the descent to H_P. The beam angle can be fairly large, and it becomes even larger as the debris comes closer, as seen in Fig. 7. The effectively needed total Δv for slowing the debris grows with increasing beam angle. An expression for the ratio $\Delta v/u$ can be derived from the trigonometric relation

$$w_f = v_c - u = \sqrt{v_c^2 + \Delta v^2 - 2 v_c \Delta v \cos\alpha} \tag{2}$$

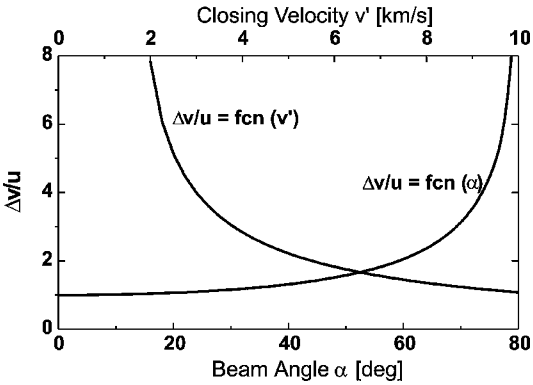

Fig. 8 Increase of the effectively necessary velocity increment Δv with respect to the beam angle α and as a function of the closing velocity.

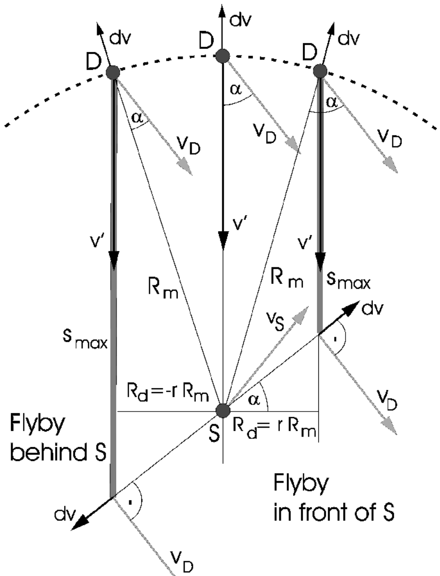

Fig. 9 Flyby of debris with velocity v_D in front or behind the laser station (simplified by neglecting the turning of the flight path during laser irradiation).

for the triangle formed by v_D, w, and dv in Fig. 5. The vectors v_D and dv enclose the angle α. In a single-pulse approximation, $w_f = w$ and $\Delta v = \mathrm{d}v$. Solving for Δv yields the relation

$$\Delta v/u = \left[v_c \cos\alpha - \sqrt{v_A^2 - v_c^2 \sin^2\alpha}\right]\Big/ u \tag{3}$$

In Eq. (3), $v_A (= v_c - u)$ is the apogee velocity of the descent ellipse. For $\alpha \to 90$ deg, the ratio of $\Delta v/u$ goes to infinity (Fig. 8). The only effect is then a turning of the particle trajectory by the angle β. If α becomes even larger than $\alpha_{\max} = 90$ deg, then the debris will be accelerated again and assume an orbit with higher apogee.

The beam angle is connected to the closing velocity by the following relation (simplified for the case $v_S = v_D = v_c$):

$$\tan\alpha = \sqrt{2\left(v_c^2/v'^2\right) - 1} \tag{4}$$

It is seen that α is small for large v'. By the introduction of Eq. (4) into Eq. (3), the necessary total velocity increment can also be expressed as a function of the closing velocity (Fig. 8). It is a measure for the required energy to remove a debris particle from LEO forever. In contrast to the intuitive expectation, slowly approaching debris is much more difficult to eliminate than debris with a high closing velocity. The larger angle α for slowly passing debris reduces both the efficient generation of the decelerating component of the impulse and the available irradiation time. The irradiation of the debris can only go on until the maximum beam angle $\alpha_{\max} = 90$ deg is reached.

Figure 9 is a comparison of the passing of the debris in front and behind the station S in the station fixed system by showing three different positions of the debris as it reaches the laser range. The debris velocity at these positions is v_{D0} in the inertial system and v_0' in the station-fixed system. The direction of the station flight path is indicated by the flight vector v_S in the inertial system. From Fig. 9, it is immediately suggestive that, for a passing in front of S, the flight distance $s_{\max}$ for α reaching just 90 deg decreases with increasing flyby distance, R_d, and hence so does the available irradiation time. The reason is the limited action radius of the laser, R_m. The situation for a flyby behind S is much more favorable. The reduced initial beam angle α first allows a more efficient impulse generation and second a much longer interaction time. Because α may even change its sign, the distance over which the debris can be irradiated with a decelerating effect can even be longer than the maximum range of the laser, R_m. Unfortunately, the flyby side cannot be chosen at will. Thus only one side of the station S may be cleared efficiently over a great distance. The situation can be improved somewhat by surrounding the station to be protected with two laser sources or relay mirrors at some distance in front or behind of it, just as is necessary for a protection against a direct hit. Only the favorable laser beam would then operate.

Debris at Different Orbit Altitudes

The laser interaction is not limited to the orbital plane of the laser. Hence, debris at other altitudes, differing by ΔH, can be reached as well. However, in this case the effective dv is reduced by the cosine of the elevation angle θ, which is defined as $\sin\theta = \Delta H/R_m$. A reasonably effective vertical range is, therefore, given approximately by two-thirds of the horizontal range. Thus, debris can be removed within an eccentric elliptic cross section around the orbit of the laser. A slight change in the transfer velocity u must be accounted for at different orbital altitudes.

Model Calculations and Characteristic Results

Numerical Model

The flight trajectory has been calculated for the assumptions laid out in an earlier section, and the following two problems have been analyzed: 1) deflection of a collision trajectory by a total angle β' so as to miss S by a safe distance, d_{flyby}, and 2) elimination of debris passing at some distance R_d by slowing it down to the apogee velocity v_A of a descent ellipse with perigee height $H_P = 100$ km. The model calculations start at the maximum radiation distance $R_m = 100$ km and end if either the required transfer velocity is reached, the necessary deflection is achieved, the maximum beam angle is exceeded, or the debris is vaporized in the meantime. The integration is carried out numerically by adding up the changes of velocity and mass for each individual laser pulse. The following parameters have been varied: closing velocity in the range of significant debris flux, that is, from 4.8 to 13.7 km/s; debris mass up to the maximum removable or deflectable size; and distance of the debris trajectory from the station S or, respectively, the offset distance of the laser source or relay mirror from the station to be protected. For comparison, the hypothetical limits, reached if the loss of debris mass by ablation or vaporization, μ, is set to zero, have been determined as well. The following sections characterize and summarize the most important results.

Results for Debris Deflection

The deflection of the trajectory for the object to miss the station requires a placement of the laser or a relay mirror some distance R_d away from the protected asset (Fig. 7). The asset is located at point E, and the laser beam is emitted or redirected from point S. During the time of laser operation, the beam angle changes from α_0' to α_1'. At this point, the summed-up deflection angle β' is large enough for the subsequent trajectory to pass E at a given distance d_{flyby}. The change of the energetic requirements for the laser with increasing R_d has been investigated. The distance $d_{\text{flyby}} = 500$ m has been chosen and is considered to be safe even for such a large structure as the ISS with its approximate diagonal extension of 150 m.

For aluminum targets, envelopes for three velocities v' are shown in Fig. 10, which describe maximum masses that can be handled in different ways. The lowest triangular regime encloses debris masses that can be vaporized completely. The next set of curves, termed

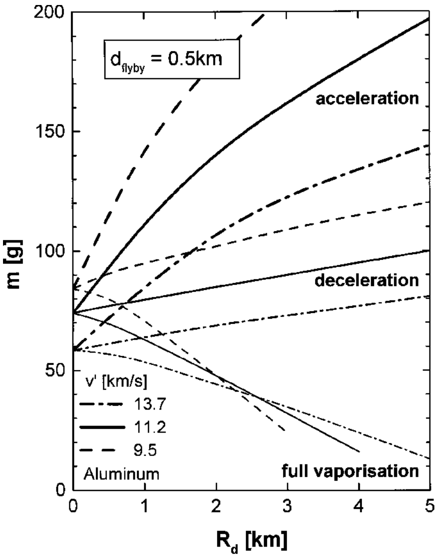

Fig. 10 Maximum masses on a collison trajectory that can either be vaporized or deflected to a flyby distance of 500 m, depending on the separation between laser beam source and protected station (aluminum target).

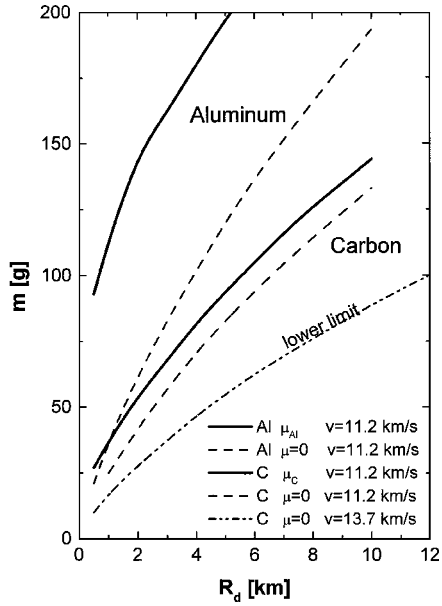

Fig. 11 Comparison of the maximum deflectable mass in the same situation as in Fig. 11, but for different material constants.

deceleration, marks the limits for masses that are not only deflected by the given distance d_{flyby} but also experience a decelerating momentum, forcing them into an orbit with lower perigee. Within the displayed range, the induced velocity increment even surpasses the transfer velocity for descent into the atmosphere and, thus, in addition to the appropriate deflection, these objects are eliminated from LEO also. However, even higher masses, up to the curve marked acceleration, can be deflected appropriately. However, during the engagement process with the laser radiation, these heavier bodies will first be decelerated and then accelerated again because the beam angle finally exceeds $\pi/2$. Such debris assumes an orbit with a higher apogee and may remain dangerous for some encounters in the future. Because S and E must move along the same trajectory, there is a difference whether S flies in front or behind E, as discussed for Fig. 9. However, as long as $R_d \ll R_m$, the difference is small. Hence, the result for only one of the two possibilities is shown.

The advantage of an increased distance for the placement of the laser from the station to safely deflect larger masses is apparent from Fig. 10. The curves for successful deflection and complete vaporization meet at $R_d = 0$, highlighting that for the direct collision threat complete vaporization is the only solution. Slower moving debris has more chances to be deflected, and higher masses can be handled. The required irradiation time outside of the regime for total vaporization depends little on R_d within the considered range. However, the vaporized mass fraction for the maximum mass decreases rapidly from 100% to between 55 and 70% as R_d is increased to 7 km and would decrease even further for a larger distance of the laser from the protected space asset.

Figure 11 shows the same situation as that in Fig. 10 for the maximum aluminum masses with $v' = 11.2$ km/s, however, now in comparison with carbon. Also included are the corresponding hypothetical cases, first with no ablation at all ($\mu = 0$) and second the ultimate lower limit for the highest probable closing velocity of 13.7 km/s. Because, for carbon, the ablation rate is already small, the hypothetical limit is only a little lower compared to aluminum. To effect a maximum protection for all practical situations and for masses up to 100 g, the distance R_d of the laser source or relay mirror might be extended to approximately 12 km. As the displacement distance R_d increases, placing of the laser or the director mirror behind the asset becomes slightly more advantageous over the opposite side. The reason is a higher initial beam angle α.

Results for Debris Elimination

For the elimination of debris by atmospheric reentry, the requirement is a deceleration of the debris by the transfer velocity u. In this case the passing distance R_d (analogous to the offset distance in the preceding section) is arbitrary, and a stronger difference arises for debris passing in front of or behind the laser source. In Fig. 12, valid for aluminum, the passing distance is normalized to the laser range as $r = R_d/R_m = \sin\alpha'$, where α' is the beam angle in a station fixed-coordinate system. Positive r denote a pass in front of the station. Again, Fig. 12 shows for three, respectively, four closing velocities the maximum mass that can be eliminated by either complete vaporization or by the appropriate deceleration. For positive r, the maximum mass decreases rapidly, both with increasing passing distance and with decreasing closing velocity. In this case, the maximum beam angle is reached after a short flight distance. For example, for aluminum debris with a velocity of 11.2 km/s, nothing can be affected beyond a distance of 60 km, even against the smallest particles. A debris mass of 100 g can be eliminated only if the passing distance is less than 7.5 km for $v' = 4.8$ km/s or less than 16 km for $v' = 13.7$ km/s. Slowly approaching debris are clearly more difficult to eliminate than faster approaching debris if it passes in front of the station.

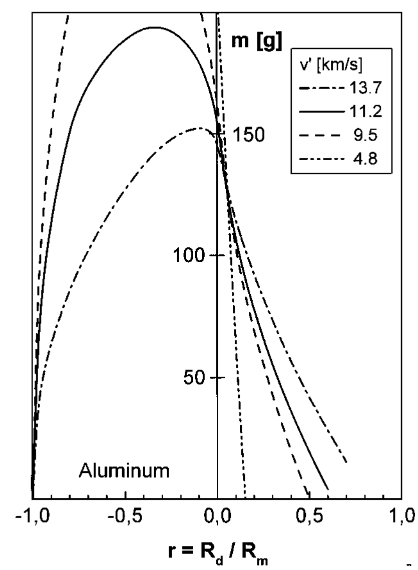

Fig. 12 Maximum removable mass as a function of the relative flyby distance for some characteristic closing velocities (aluminum target).

A passing behind the laser source (negative r) dramatically increases the manageable mass and the trajectory distance because the beam angle remains favorable even when the debris has already

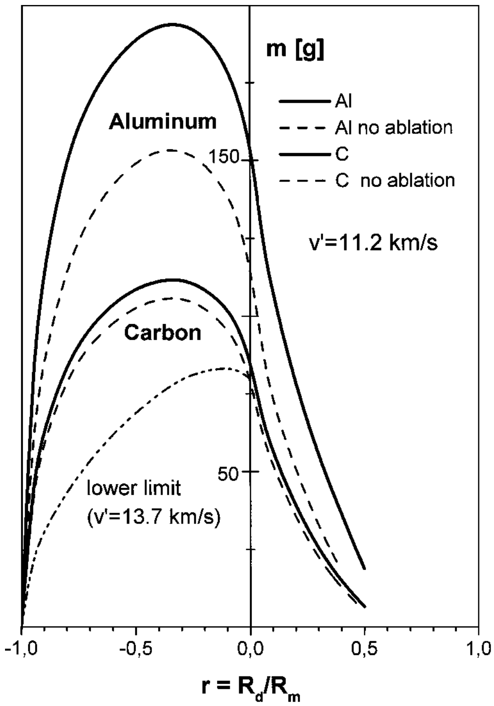

Fig. 13 Maximum removable mass for targets with different material constants.

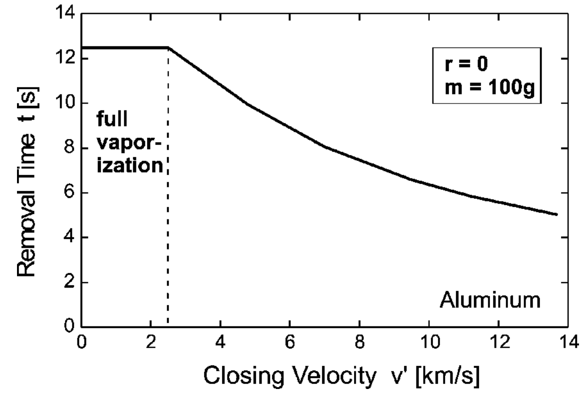

Fig. 14 Necessary interaction time for the removal of a debris mass of 100 g as a function of the closing velocity and for a very close flyby: for $v' < 2.5$ km/s, the debris is removed by complete vaporization before the transfer velocity is reached.

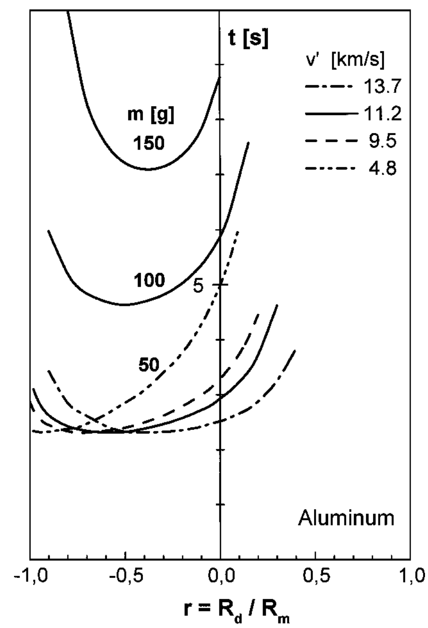

Fig. 15 Necessary irradiation time for the elimination of different masses, closing velocities, and relative flyby distances in the case of aluminum targets.

passed the station S. The situation also changes with respect to the closing velocity in the sense that slower moving masses can be handled over a very long time, and hence, they may be quite large. At a most favorable flyby distance of about 30 km, a maximum debris mass of almost 200 g with $v' = 11.2$ km/s can be eliminated. A mass of 100 g can be downed in the least favorable situation with the highest closing velocity of 13.7 km/s outward to a trajectory distance of 70 km.

In Fig. 13, the results for aluminum are compared with those for carbon. It is seen that the removable mass drops approximately with the ratio of the coupling coefficients of the two materials. For very small r, a mass of 156 g of aluminum debris with $v' = 11.2$ km/s could be removed, but only 86 g of carbon. To demonstrate the effect of the mass loss of the target, the hypothetical limits for no ablation are again included in Fig. 13. Keeping the coupling coefficient fixed, but reducing the ablation rate μ to zero, also reduces the maximum removable masses. Clearly, objects with higher initial mass can be removed if more mass is ablated per laser pulse. As was the case with deflection, for carbon the difference becomes only marginal because of the already small ablation rate. At $r = 0$, the mass limit drops to 116 g for aluminum and to 80 g for carbon. At closing speeds above 11.2 km/s, 100 g of carbon is removable only in a small range of negative r. The decrease in maximum mass with the ablation rate is found to be almost linear, thus allowing easy interpolation for other ablation rates. Finally, the masses for a closing velocity of 13.7 km/s without any ablation are included in the graph as well. Based on the coupling coefficient of carbon, the curve represents a lower limit for all relevant encounters and materials.

The energy consumption for the laser increases proportionally with the debris mass and with the available time because every second an energy of 100 kJ is transmitted to the target. Depending on the actual situation, it may not be economical to attack massive debris that is far away. An example of the dependence of the necessary laser operation time on the closing velocity is given in Fig. 14 for the special case of 100-g Al passing very close to the station ($r \to 0$). Whereas for the maximum considered velocity of $v' = 13.7$ km/s of a 100-g particle only 5 s of operation time is required due to the more favorable beam angle, this time grows to 12.5 s as the closing velocity is reduced to 2.5 km/s or less. In this case, the elimination occurs by total vaporization. For the most frequent velocity of 11.2 km/s and for three debris masses, 50, 100, and 150 g, Fig. 15 shows how the required laser operation time and energy consumption change with the normalized distance r. On the left-hand side of the graph, the required time, in particular for the smaller masses, is fairly independent of r over a broad range. Furthermore, in this range it also depends little on the closing velocity, as long as the velocity does not become too small and the operation limits are not approached. Otherwise, the operation time increases drastically. The variation with the closing velocity is indicated in Fig. 15 for a debris mass of 50 g. The inverse dependence with the velocity as demonstrated in Fig. 14 holds actually for all relevant passing distances.

The fraction of vaporized mass is directly related to the fraction of the actual operation time to the time necessary for total vaporization: 50, 100, and 150 g of aluminum would be totally vaporized in 6.25, 12.5, and 18.75 s, respectively. Figure 16 shows the fraction of vaporized mass for $v' = 11.2$ km/s for the maximum removable mass as well as for three distinct masses. The vaporized mass fraction is very similar in all cases. It increases also with r and approaches 100%. The minimum of about 40–50% of vaporized mass and, thus, the minimum of the required total energy is found for the maximum mass at a passing distance between 5 and 15 km behind the station. For smaller masses, the minimum is shallower and extends farther to negative r. All of these numbers presume the ablation rate of 80 μg/J of aluminum or, for the given pulse energy and repetition rate, of 8 g/s. The mass limit changes, of course, with this number.

Table 2 Power effects on maximum masses for elimination

Pulse energy, kJ	Frequency, Hz	Maximum mass $r = 0$, g	Maximum mass $r = -0.6$, g
1	100	158	181
1	50	80.5	90.5
0.5	100	55.5	63.5

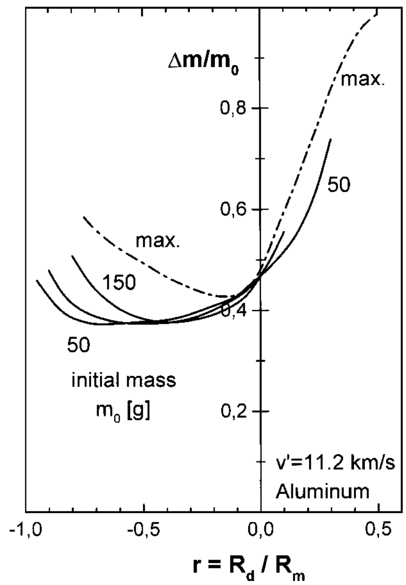

Fig. 16 Fraction of vaporized mass for different initial masses, a closing velocity of 11.2 km/s, and aluminum targets.

Scaling

In the preceding section it was shown how a change in the laser–material interaction parameters c_m and μ affects the system capabilities. These parameters are functions of the debris material, but also of the laser wavelength, the pulse duration, and the intensity at the target, as already described. In particular, the difference in the selected two coupling coefficients shows the trend in removal performance if a proper combination of laser parameters, that is, wavelength, pulse length, and intensity, and debris material yields a higher c_m value. Other parameters may be changed at will for scaling purposes: These concern the assumptions for the orbits, in particular, the orbital height and eccentricity, and the power characteristics of the laser. Different orbital characteristics arise from 1) another station orbit altitude, 2) a higher perigee of the debris target orbit, and 3) highly eccentric initial debris orbits. All of these modifications will result in a different transfer velocity u. If, for instance, the debris is allowed to have a remaining lifetime of up to one week, a perigee altitude of 200 km may suffice,[31] and only 85 m/s is needed for the velocity change at the 500-km orbit. Let the flyby distance be small ($r = 0$) and the closing velocity be 11.2 km/s, then the maximum removable mass of aluminum rises from 158 to 197 g. On the other hand, if the laser orbit were at 2000 km, the required transfer velocity would be approximately 450 m/s, resulting in a drop of the maximum mass to 81 g under otherwise similar conditions.

The average power of the laser can be changed by either changing the pulse energy or the pulse frequency. To demonstrate the effect of such alterations Table 2 summarizes the removable aluminum masses for the following conditions: elimination for two flyby distances at $r = 0$ and -0.6 with $v' = 11.2$ km/s and $u = 115$ m/s. For halving the average power the effect of the pulse energy is much more dramatic than for halving the pulse frequency. The lower energy reduces the masses to about one-third compared to one-half for the lower frequency. The reason is that the lower pulse energy of 500 J results in a reduction of the laser range by the square root of the energy ratio for otherwise unchanged radiation parameters at the target. Hence, $R_m = 70$ km has been assumed for this case. By the reduction of R_m, the dependence of the maximum masses on the power becomes nonlinear. Table 3 presents similar results for the

Table 3 Power effects on maximum masses for deflection

Pulse energy, kJ	Frequency, Hz	Flyby distance, km	Maximum mass, g
1	100	0.5	197
1	50	0.5	98
1	100	1.0	147
1	50	0.25	156
0.5	100	0.5	98

deflection capabilities. In this case a separation of the relay mirror from the laser station of 5 km has been selected. The effect of a different flyby distance is also included in Table 3.

Clearing Time for LEO

With the obtained data it is possible, in principle, to extend the integration and calculate the number of eliminated debris particles and the necessary total energy as a function of the time in orbit. For this calculation, the object density as a function of the inclination distribution or of the velocity spectrum (Fig. 6) must be taken as initial condition, together with the size distribution (Fig. 4). Finally, a further refinement would include the material spectrum.

A positioning of the laser on or near the space station does not only allow clearing out a tube around the orbit of the laser with a diameter according to the effective laser range. In fact, if the orbit of the station is considered stationary in space, there exists a relative azimuthal drift of the debris orbits that depends on their inclination. This motion is a consequence of the oblateness of the Earth, which leads to a precession shift of every inclined orbit in the azimuthal direction. Therefore, new debris constantly moves into the range of the laser. Also the difference in orbital velocity for different altitudes makes new debris material accessible to the laser in the direction vertical to the orbital plane. Finally, debris is seeping gradually down into the range of the laser from higher orbits due to residual atmospheric friction.

A crude estimate can be made on the clearing time of the shell accessible by the laser. For every revolution around the Earth, a (eccentrical) tube with a cross section of approximately 70×70 km may be cleared. Because of the differential velocities, this tube will be partly refilled after one revolution. If the refilling per revolution is assumed to be 25%, then it takes 3530 revolutions or 230 days to engage most of the debris ($\sim 10^4$ objects) within a shell of 70-km thickness. After this time, only a fraction will be left over for which the phase shift was too large (debris being on the opposite side of the Earth and not catching up to the station within that time) or the crossing angle was too small. This leftover fraction will have to be eliminated later. Another estimate concerns the required total power for this initial clearing. According to a more recent debris model,[5] the object flux for fragments in the diameter range from 1 to 15 cm is approximately 44×10^{-7} objects/m^2 year. During the first phase of operation, the object flux sums up for the assumed elliptic cross section to 1.6×10^4 year^{-1} or about 1 object every 35 min. If the average fragment has a diameter of 3 cm and a mass of 5 g, of which 3.6 g has to be vaporized, one needs 45 kJ per object. Let the laser have a total efficiency of 2%; then only slightly more than 1 kW of electric power has to be collected and stored continuously in the early phase from solar radiation, for instance (energy for support systems is not included). At a later stage of technological development, it may be possible to put a laser system of a comparable size onboard an autonomous spacecraft with an elliptic orbit between 400- and 2000-km altitude and with a more favorable inclination with respect to the bulk of the debris. Such a system would then be capable of cleaning up all LEO of the small debris within a few years.

System Implementation Considerations

An operational debris removal system comprises more than just a pulsed high-power laser. In fact, to some extent it is similar to a laser weapon system, such as, for instance, the airborne laser of the United States, only at a much smaller size. The debris removal system consists of a surveillance system to detect and track debris for a range exceeding the effective laser range, a system to aim and deliver a focused laser beam to the target and keep it locked to it, and finally some data processor to calculate the debris trajectory before and after the laser interaction. Furthermore, operational power must be provided for the laser itself and for all of the subsystems. Of course, as a rule, the laser shall not be operated if by some constellation the beam could harm another operational asset. This requires further means to exclude such an incidence.

No attempt has been made at this point to estimate size and costs of a space-based debris removal system. The cost will have to include the development, manufacturing, transportation and deployment, and the maintenance. Among these issues, transportation to space may be the most crucial and of equal importance to the technical feasibility. As the technical maturity is approached, installation and maintenance costs have to be addressed and balanced against the potential gain of security for either ground- or space-based option. The technology to establish such a system is largely at hand today, although some power upgrading and the adaptation to the space environment will need further developmental work. It is believed that the total size of a system will fit in at most one or two shuttle loads.

Particularly difficult and even political questions concern the profit in terms of saved satellites, as well as the institution that operates the system. Our modern society depends more and more on a flawless stream of data from space. The interruption of the data flow from a damaged satellite may prompt even higher losses for dependent services on the ground. Fortunately, only little damage by debris has occurred so far. Maybe this lucky circumstance and the expected development and deployment costs will prevent the large spacefaring nations from taking actions toward installing a debris removal system in the very near future. On the other hand, significant amounts of money flow into research for hardening the space station, an effort that can produce only limited assurance against a fatal event. This money would be better invested into some means that overcomes the threat all together. However, a single nation will most likely be highly reluctant to provide a system that serves other nations in equal manner without being compensated for this service. (There exist counterexamples though; for instance, the global positioning system.) On the other hand, as more and more satellites of private companies populate LEO, interest in keeping these satellites alive and healthy will rise. If a collisional incidence occurs, for instance, by a leftover space object, and its former owner can be determined, the problem boils down to a (possibly international) legal affair. As the number of fatal incidents increases due to the growing number of debris, the financial pressure from equally increasing insurances rates will support efforts to establish some more efficient means against the possibility of collisional losses: first by consequently avoiding the production of debris and second by active means for its remediation. At present, the only practical procedures of collision avoidance beside the continuous observation of space and the issuance of early warnings are to adjust, at additional costs, the flight path and maneuver to trajectories that avoid, or minimize, the possibility of a collision. No international organization is actually operating a generally agreed upon monitoring system. Presently it is the U.S. Space Command, a national and even military organization that maintains the premier resident space objects catalog. Recently, Ailor[3] raised the question about who in the future will pay for the continuous operation and upgrading of the sensor systems, the data acquisition hardware, and the provision of risk data for customer demands.

The solution can only lie in the foundation of an international institution. It could well be a private consortium with satellite operators and satellite insurance companies as members. The problem that has to be resolved is the question how all users of space can be motivated or forced to contribute to the establishment and operation of an independent space observation system. Once such an organization is established, however, it would be natural to extend its tasks from the passive observation and warning service to an active one that attempts to remedy physically the collisional threat by actively reducing the number of debris. Certainly there are many implications associated with the construction of such an organization, as has been outlined by Ailor[3] in detail. Therefore, he calls for a quick start "to develop a plan to ensure availability of robust situational awareness services." It is appropriate to include in this plan the option to establish an active debris removal system. The most meaningful of such systems for the large number of small debris is one based on laser radiation interaction.

Conclusions

A repetitively pulsed, space-based laser with an average power of about 100 kW and a wavelength in the 1–2-μm region appears to be a valuable tool to mitigate the serious threat of a fatal collision of a space asset such as the ISS with debris up to at least 10 cm in diameter. In contrast to a similar, but much more complex, installation on Earth, it cannot only defend a station against an immediately threatening collision by vaporizing or deflecting an approaching object, it is also capable of entirely cleaning up a shell in which the laser is orbiting. Aluminum and carbon have been selected as typical debris materials for sample computations: The assumption has been made that the debris detection system and the beam direction system allow interception approaching debris at 100-km distance. Under favorable conditions, debris of masses of 100 g at a passing distance of up to 70 km can be removed from orbit. The maximum laser energy for this task is less than 700 kJ per aluminum particle. A complete removal of debris is achieved by reducing the orbital velocity of the debris, thereby sending it down into the atmosphere where it burns up. For this purpose, a momentum is exerted on the objects by ablating a fraction of its mass. The inspection of the geometrical situation in the orbital plane showed that great differences in demand exist. Objects with a low closing velocity are more difficult to remove. The practical range of the laser depends on the side on which the object passes the laser source or, alternatively, a relay mirror for the laser beam. To deflect a direct-hit trajectory of an object by, for instance, 500 m, the effective laser beam source or a relay mirror should coorbit the protected station at a distance of up to 12 km. According to the results of the calculations, the chosen laser power of 100 kW is more than sufficient to deal with debris of size up to 10 cm. It has been shown how a reduction in laser power and in the requirements for the transfer velocity will change the capabilities of the system.

The results encourage suggesting that a smaller, space-proof system be deployed at an early stage of the ISS lifetime to prove the concept of protecting the station and to serve as a debris sweeper to a minor extent. The system could be deployed and operated by an international organization that should be established for the control of space traffic.

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