SPACE-BASED LASER ABLATION FOR SPACE DEBRIS REMOVAL

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ABSTRACT

Space debris objects between 1 and 10 cm form a major threat to both active and defunct spacecraft. This research investigates the performance of a space-based laser system to remove such debris objects. The laser system is placed in a 800 km Sun Synchronous Orbit and consists of a 20 kW laser that shoots 600 J energy pulses with a repetition frequency of 33.33 Hz. The system is able to detect and track debris objects in-situ using a 1.5 m mirror from 800 km distance. From a distance of about 500 km, the laser fluence on the targets is sufficiently high to trigger ablation, which decelerates the debris objects and reduces their lifetime. The concept is tested on debris objects orbiting at higher and lower altitudes and targeted from different azimuth angles. For all geometries investigated, the laser is capable to significantly reduce the lifetime of the debris object. Extrapolating the results for longer periods of operation, the laser can be expected to provide a significant reduction of the population of debris objects between 1 and 10 cm.

Keywords: Space Debris; Debris Removal; Laser; Ablation.

1. INTRODUCTION

Every launch of any space mission generates fragments of debris in space. A method for waste-removal in space has never been set in place, resulting in the current scenario where an estimated 900,000 debris fragments larger than 1 cm are orbiting Earth, of which every single one poses a serious danger for satellites that are active [1]. A specifically difficult sub-population is found in debris fragments with sizes between 1 and 10 cm, which are large enough to potentially break up a spacecraft in a collision, but are too small to monitor from ground so that satellites can not avoid them [2]. Reducing this set of small-scale LEO debris objects is paramount for a safe future of spaceflight.

2. ALTERNATIVE TECHNIQUES

Large debris objects like defunct satellites form the biggest risk of creating fragmented debris. However, small debris objects form the biggest threat to creating break ups [3]. In recent years, more and more concepts have been designed to remove large debris objects: the debris gets captured with nets, harpoons or a robotic arm, after which both the debris object and the servicer satellite spiral into the atmosphere and burn up [4]. These methods are inefficient and will never work for the removal of numerous small debris objects in LEO, if only because of their size and numbers. Concepts for the removal of small-scale debris objects on the other hand are scarce. A ground-based laser system would not work: objects with sizes below 10 cm are too small to track from Earth. It is intended to research the performance and feasibility of a space-based laser system on the LEO debris population. This method is currently the only plausible technique to remove debris fragments below 10 cm since it monitors debris objects 'in-situ' and thus has no dependence on a catalogue based on ground-station observations. An in-orbit laser system is a promising technique since it does not require contact with the debris objects and can target objects in a continuous fashion when powered by solar panels.

3. CURRENT STATUS

The approach to lower debris objects using space-based laser ablation was first brought forward in 1991 [5]. In many ways, the design is still the same as current proposals: an in-orbit satellite equipped with a laser and optics to ablate an object and a subsystem that controls the detection target acquisition. Various adaptations of a space-based laser have since then been proposed. A research from 2014 posed that an ICAN laser with kHz repetition frequency is capable of de-orbiting debris fragments with sizes between 1 and 10 cm after one encounter [6]. Another concept from 2014 named L'ADROIT claimed that an ultraviolet laser with 20-40 kW placed in an elliptical orbit could achieve the same results [3]. However, these papers report theoretical conclusions and assume that every encounter will have a head-on geometry. This paper intends to contribute to the literature of orbital laser systems how a hypothetical laser performs in LEO, taking into account the exact (and changing) geometry with which LEO debris objects are targeted.

4. ORBITAL LASER SYSTEM

The space-based laser system will track debris objects as it encounters them in orbit. The design of the subsystem for the target acquisition is adopted from [7]: first, the reflected sunlight of a debris fragment is detected using a large 60^o FOV telescope. Then a second smaller telescope will send low energy laser pulses while tracking the object. The reflected laser photons off the target have a much higher Signal-to-Background Ratio (SBR) and determine whether the target is indeed a piece of space debris. In this way, the system will never accidentally ablate an unwanted object. Using this method for the target acquisition, debris objects can be detected from 800 km. If a successful target is selected, the laser will ablate the object and alter its velocity. For some geometries, this velocity change may cause the object to burn up in Earth's atmosphere within half a revolution. For other less optimal geometries, the orbital lifetime of the target can still be reduced.

4.1. Ablation

Ablation is achieved when the energy density at the target surface exceeds a certain ablation threshold, specific to the target material. The energy density of the laser is called the fluence and is defined as follows [3]:

$$\Phi = \frac{E_{pulse}}{\frac{1}{2}\pi w(L)^2} = \frac{4 \cdot E_{pulse} \cdot D_{eff}^2}{\pi \cdot M^2 \cdot a^2 \cdot \lambda^2 \cdot L^2} \tag{1}$$

in which E_{pulse} is the laser energy pulse and the laser beam width $w(L)$ is defined as the radius from the center of the beam where the laser intensity has reduced by a factor $1/e^2$. The laser beam width further depends on the laser beam quality M^2, the laser wavelength λ, the propagation distance L, the diffraction constant a and the effective mirror diameter D_{eff}, which is defined as the fraction of the total mirror that redirects the laser beam.

With the expression for the energy per area of the laser beam at a distance L, the exerted force on a target area can be described [8]:

$$F_{thrust} = \Phi_{eff} \cdot A_{target} \cdot C_m \cdot f \tag{2}$$

where A_{target} is defined as the cross-sectional area of the object, C_m is an experimentally determined material specific coefficient that shows how much power is converted to thrust, f is the pulse frequency and the relation $\Phi_{eff} = T_{eff} \cdot \Phi$ is implemented, where T_{eff} accounts for system performance losses such as atmospheric disturbances or laser attenuation.

4.2. Laser parameters

Table 1 shows the parameters of the space-based laser system. Using 100 m^2 of solar panels with state-of-the-art power generation of 0.27 kW/m^2 results in a total system power of 27 kW, of which 7 kW is reserved for the electrical subsystem. The remaining 20 kW is used to shoot 600 J energy pulses at a 33.33 Hz frequency. Other parameters are taken from [3].

Table 1. Parameters of the laser system.

Parameter	Value
$P_{subsystems}$ [kW]	7
P_{laser} [kW]	20
E_{pulse} [J]	600
f_{pulse} [Hz]	33.33
τ_{pulse} [s]	10^{-10}
D_{eff} [m]	1.5
λ [nm]	335
$C_{m,alu}$ [N/MW]	128
A_{solar} [m^2]	100
T_{eff}	0.9
M^2	2.0
a	1.27

Table 2. Orbital elements of the laser system.

h [km]	e	i [°]	ω [°]	Ω [°]	ν [°]
800	0.0	98.0	0	0	0

Table 2 shows the orbital elements of the laser system. The system will be placed in a non-elliptical Sun Synchronous Orbit (SSO) at 800 km altitude and 98^o inclination. This configuration suits this feasibility study for multiple reasons: this SSO is densely populated with debris objects so that the laser is able to engage with objects in a large altitude range and from all possible geometries. Next to this, the orientation w.r.t. the Sun will ensure optimal sunlight to solar panels and the black background will result in an optimal SBR.

5. METHODOLOGY

The laser is tested on debris objects from various arbitrary geometries. After each encounter, the reduced lifetime of the target is computed and compared to its nominal orbital lifetime to check the effects of the laser interaction.

5.1. Propagation

The orbits are propagated using a Runge-Kutta 4 model, which proved sufficiently accurate for the purposes of this study. The laser orbit and the debris objects are influenced by Earth's gravity, SRP, aerodynamic effects and luni-solar perturbations. The atmosphere is assumed to have an exponential profile with $\rho_0 = 2.51 \cdot 10^{-10}$ kg/m^3 and a scale height H of 82.0 km, leading to realistic densities at the corresponding orbits. A typical encounter will have the following steps: First, the orbits of the laser and debris object are initialised so that they will encounter each other with a certain geometry. The orbits are propagated with a stepsize of 10 s until the relative distance is below 800 km and the debris object can be 'detected'. Now the orbits will be propagated with a stepsize of 1 s to more accurately follow the interaction. The laser will focus its beam on the target and ablation is achieved at a distance of about 500 km. The propagation will stop when one of the following termination conditions are satisfied:

- $\mathbf{d}_{rel} \cdot \mathbf{v}_{rel} \geq 0$. When the scalar product of the relative distance and the relative velocity becomes positive, this implies that the debris object has passed the laser as it is now moving away from it. Since this geometry will only increase the orbital energy of the target, this condition should not be violated.
- $\omega > 2^o/s$. As the laser system tracks the debris object, it will have to rotate to keep following it. The propagation should be terminated when the laser has to rotate faster than the state-of-the-art of steering wheel mechanics of $2^o/s$ [3].

Figure 1 shows a schematic of an interaction between the laser and a target debris. The definition for the angular rate is given as follows:

$$\omega = \frac{v_{trans}}{L_{rel}} = \frac{v_{rel} \cdot sin(\beta)}{L_{rel}} \tag{3}$$

where β is the angle between the relative distance vector and the debris orbit, v_{rel} is the relative velocity and L_{rel} is the relative distance.

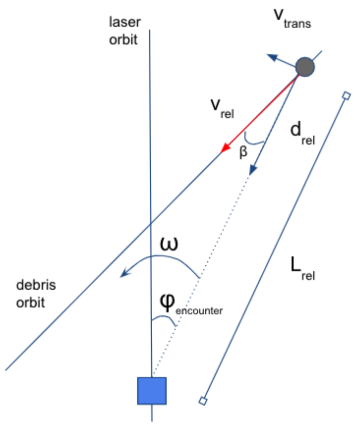

Figure 1. Interaction between laser and debris object. v_{trans} will determine the angular rate of the laser steering wheel.

The distance where the angular rate limit is exceeded is plotted for five scenarios in Figure 2. The technical limit of 2^o/s is plotted as an extra horizontal line. In the head-on scenario, the laser exceeds the limit at a relative distance of 63 km. When there is a difference in altitude, the technical limit is exceeded much sooner. However, whether this difference is above or below the laser does not influence the outcome, which can be seen in Figure 2 by noting that the two sets of lines overlap. Moreover, geometries where the debris is targeted from a smaller azimuth angle will exceed the angular rate limit sooner. For an azimuth angle of 30^o and 60^o, the limit is exceeded at a relative distance of 206 and 197 km respectively. This is because the relative velocity of the interaction is lower for encounters at higher azimuth angle, which also results in a lower demand for the angular rate (Equation 3).

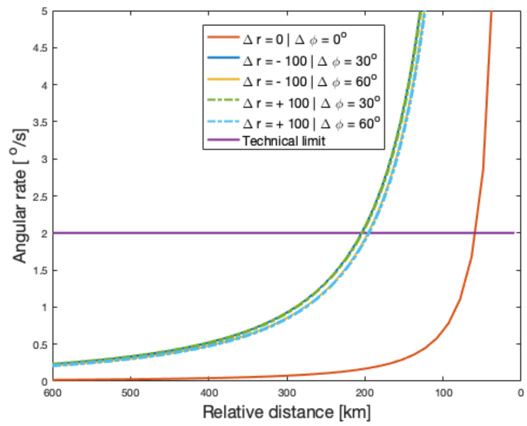

Figure 2. Angular rate limit for five scenarios with different geometries.

5.2. Orbital lifetime

The main scope of this study is to compare the orbital lifetime of the debris objects before and after the laser interaction, so the lifetime computation will be essential. To first order, the orbital lifetime of LEO objects can be assumed as follows [9]:

$$T_{life} \approx -\frac{T_{period} \cdot H}{\Delta a_{rev}} = \frac{T_{period} \cdot H}{2\pi C_D (\frac{A}{m}) \rho a^2} \tag{4}$$

with T_{period} the time of one revolution at semi-major axis a, H the atmospheric scale height, Δa_{rev} the change in semi-major axis per revolution, ρ the atmospheric density at a, C_D the drag coefficient and (A/m) the Area-to-Mass Ratio (AMR) of the object. However, Equation 4 does not account for elliptical orbits with varying atmospheric density. In those cases, the average density is taken as if the object orbits at an effective circular semi-major axis [10]:

$$a_{eff} = r_{perigee} + 900 \cdot (e)^{0.6} \tag{5}$$

where e is the orbital eccentricity. Equation 4 shows that orbital lifetime of an object depends on its AMR. Therefore, the laser system will be tested on three objects

Table 3. Three objects to test laser performance.

Diameter [cm]	**1**	**5**	**10**
AMR [m^2/kg]	0.16	0.07	0.04
Area [m^2]	$7.85 \cdot 10^{-5}$	$1.96 \cdot 10^{-3}$	$7.85 \cdot 10^{-3}$
Mass [kg]	$0.5 \cdot 10^{-3}$	$30 \cdot 10^{-3}$	$200 \cdot 10^{-3}$
ρ_{debris} [g/cm^3]	0.952	0.458	0.380

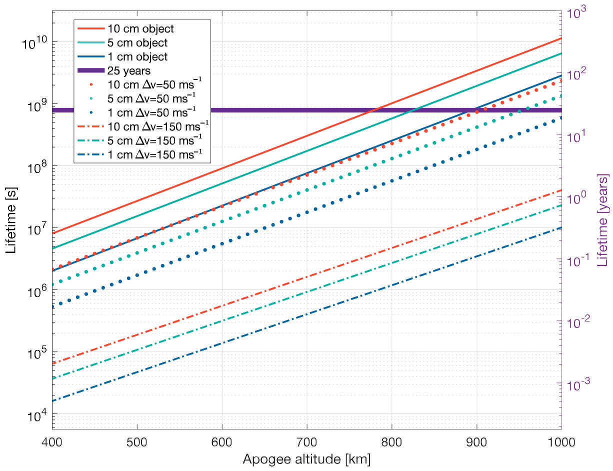

Figure 3. Lifetime for assumed Δv of 50 and 150 m/s on three objects with different AMR.

with varying AMR, all within range of the current LEO debris small-scale debris population; the main characteristics of these three objects are given in Table 3.

The nominal orbital lifetime of the three objects, as well as the lifetime after an assumed Δv are plotted in Figure 3. It can be clearly seen that the lifetime of the three objects depends on altitude. The horizontal line shows the IADC determined guideline that states that any object in LEO should de-orbit within 25 years after the mission has ended. All 10 cm objects below 775 km, 5 cm objects below 825 km and 1 cm objects below 880 km already follow the IADC limit. The lifetime of all objects orbiting at higher altitudes will have to be reduced in order to adhere to the 25 year limit. The three dashed and striped lines belong to the lifetimes of the elliptical orbits of the debris objects after an assumed Δv was applied of 50 and 150 m/s respectively.

6. RESULTS

There only exist a limited number of possible geometries from which the laser system can target an object: the coplanar geometry where both objects orbit in the same plane and the non-coplanar geometry where laser system

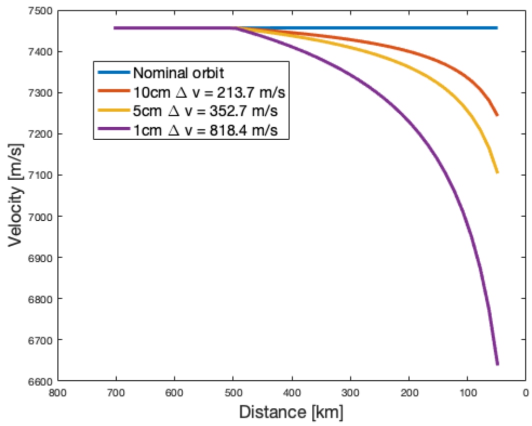

Figure 4. Δv produced by laser on three debris objects in head-on geometry.

has an azimuth angle ϕ w.r.t. the target orbit.

6.1. Coplanar, identical altitude

First, the results will be shown for the head-on interaction, since these cover the most straightforward physics. Figure 4 shows the generated Δv on the three objects from Table 3. Since the produced thrust in Equation 2 is proportional to A_{target}, the produced deceleration on the target will be proportional to A/m, which is the object's AMR. This is clearly shown in Figure 4, where the 10 cm object is slowed down by 213 m/s, but the 1 cm object is slowed down by 818 m/s. Figure 3 shows that such Δv's will de-orbit the debris object within half a revolution. Although these results are very promising, it should be noted that the head-on geometry has a rather small probability of occurring w.r.t. other geometries [3]. However, it does show the potential of the laser system.

6.2. Coplanar, different altitudes

Figure 5 shows the results of the laser interaction with a 10 cm debris object that is orbiting 50, 100 and 200 km above and below the laser system. To show the performance limits of the system, only the results on the 10 cm object are shown, knowing that the 1 and 5 cm object will be decelerated even more. The debris objects have different orbital velocity due to their different altitude. It can clearly be seen that the angular rate termination condition is violated sooner for debris objects with larger difference in orbital radius. For the objects at ± 100 km this is at a relative distance of about 200 km, but the objects at ± 200 km already become untrackable at a relative distance of about 300 km. The resulting difference in produced Δv on each object is shown in Table 4. As expected, the highest Δv values correspond to the objects orbiting closest to the laser. The orbital lifetime of the objects before and

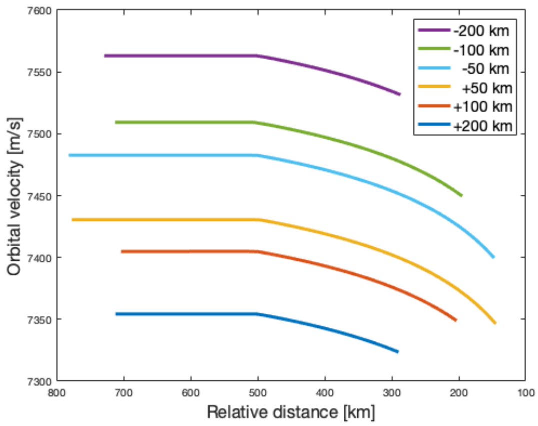

Figure 5. Δv produced in coplanar geometry with 10 cm debris objects orbiting higher/lower than laser system.

Table 4. Lifetime of 10 cm debris object before and after laser interaction.

$\mathbf{h}$[km]	$\mathbf{\Delta v}$[m/s]	$\mathbf{T_{before}}$[yrs]	$\mathbf{T_{after}}$[yrs]
600	34.0	3.3	1.4
700	65.0	11.3	1.5
750	92.3	20.7	0.9
850	93.5	69.7	2.8
900	61.1	127.8	17.7
1000	33.2	429.7	163.5

after the interaction are also listed. All objects have their lifetime reduced to below 25 years, except the object orbiting at 1000 km altitude. All objects orbiting below 750 km naturally adhere to the 25 year guideline. However, the interactions on these objects are still highly useful as any lifetime reduction of space debris objects should be taken as a success.

6.3. Non-coplanar, identical altitude

It will be useful to first discuss the maximum azimuth angle from which it can still be feasible to target debris objects. Figure 6 shows a schematic of an interaction where the laser targets the debris object from an azimuth angle ϕ. Naturally, the FOV of the satellite dictates the maximum angle at which debris objects can be detected. The state-of-the-art FOV is around 60^o, so debris objects will be detected between $-30^o < \phi < 30^o$. This implies that the maximum azimuth angle at impact will be 60^o. Debris objects with higher values than this can not be detected by the satellite.

Figure 7 shows the achieved Δv when the debris object orbits at the same altitude but is targeted from azimuth angles ranging from 10^o to 60^o. The lifetime reduction

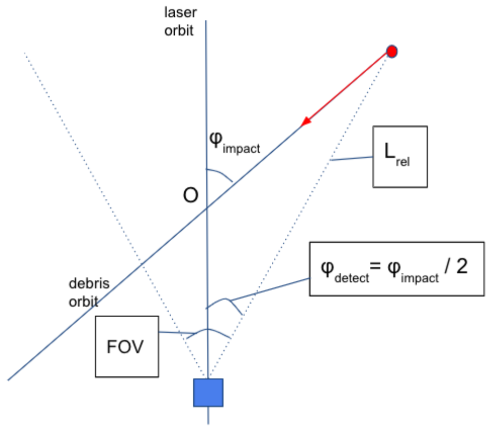

Figure 6. Schematic of FOV of satellite.

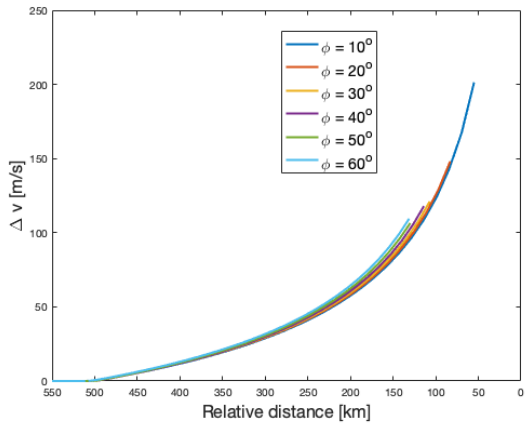

Figure 7. Δv produced on 10 cm debris objects in non-coplanar geometry with same altitude.

for all objects is listed in Table 5. The nominal lifetime of the 10 cm objects at 800 km altitude was 38 years, but the laser interaction reduces the lifetime of all objects to below one year. The object targeted at azimuth angles of 10^o and 20^o even have their lifetime lowered below 2 months. The larger the azimuth angle at which the object is targeted, the larger the component of the laser beam will be in an ineffective direction, which will result in lower Δv values. However, even when an object is targeted from 60^o, a significant lifetime reduction is achieved. The Δv at 60^o is higher than that at 50^o. The lower relative velocity results in a longer interaction time, which translates to a larger Δv.

6.4. Non-coplanar, different altitude

The most frequently occurring geometry will be where the laser and the debris object will have a difference in orbital altitude and there is an azimuth angle. Figure 8 shows the four sets of three lines, corresponding to a 10

Table 5. Relative velocities and resulting interaction time of geometries with different azimuth angles.

ϕ [°]	Δv[m/s]	T_{before}[yrs]	T_{after}[yrs]
10	201.4	38	0.002
20	148.2	38	0.18
30	121.1	38	0.55
40	117.9	38	0.62
50	106.5	38	0.97
60	109.5	38	0.86

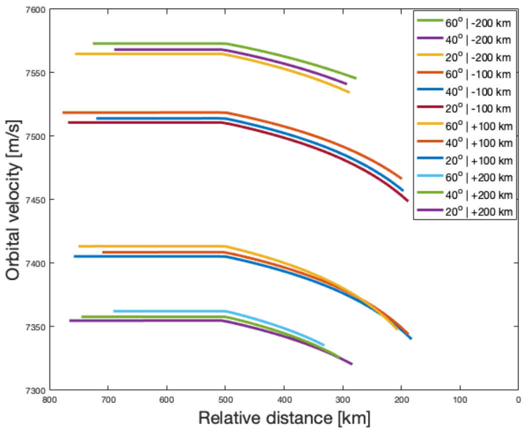

Figure 8. Δv produced on 10 cm debris objects in non-coplanar geometry with debris orbiting higher/lower than laser system.

cm object targeted from three different azimuth angles at 100 and 200 km above and below the laser. Again, it can be clearly seen that the angular rate condition is violated sooner when there is a larger difference in altitude. The lifetime reductions of the objects are listed in Table 6. The lifetimes of all objects are lowered below the 25 year guideline, except for the object orbiting at 1000 km altitude. This does not mean the system fails to target high altitude objects. First, the objects will be lowered to a region where the laser system can target it a second time more successfully. Second, only the results on a 10 cm objects are shown here. The laser system will be much more effective on a 1 cm object orbiting at 1000 km.

7. CONCLUSIONS AND RECOMMENDATIONS

This paper has researched the feasibility of decelerating LEO space debris from arbitrary geometries using a space-based laser ablation system. From a head-on geometry, all objects are de-orbited within half a revolution. When the debris object orbits at the same altitude as the laser but is targeted from an

Table 6. Results from non-coplanar interactions with altitude difference.

h [km]	ϕ [°]	Δv[m/s]	T_{before}[yrs]	T_{after}[yrs]
600	20	30.4	3.36	1.38
600	40	27.2	3.36	1.75
600	60	27.5	3.36	1.73
700	20	62.1	11.28	1.69
700	40	52.8	11.28	2.36
700	60	52.2	11.28	2.41
900	20	65.1	127.79	15.1
900	40	54.6	127.79	22.69
900	60	52.3	127.79	24.75
1000	20	34.4	429.74	156.47
1000	40	27.6	429.74	200.56
1000	60	26.9	429.74	205.66

azimuth angle, all objects will still de-orbit within one year. The laser system gets less effective for objects with increasing altitude difference. However, the most important result is that the laser can still cause significant effects to debris fragments that orbit 200 km higher or lower. Even if some interactions did not lower the lifetime below 25 years within one interaction, a second interaction will most likely achieve the desired result. Next to that, the results that were presented were for a 10 cm object, which will only be a fraction of the complete debris population. Since lifetime is inversely proportional to the AMR, the interactions on debris objects with higher AMR will result in even lower lifetimes.

To really inspect how well the laser system could perform in physical reality, a simulation should be run for a long time period with different debris objects representing LEO debris objects. This will show to what extent the laser system can ensure the safety of the LEO region.

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