POTENTIAL OF USING GROUND-BASED HIGH-POWER LASERS TO DECELERATE THE EVOLUTION OF SPACE DEBRIS IN LEO

Stefan Scharring(1), Jürgen Kästel(1), Gerd Wagner(1), Wolfgang Riede(1), Erik Klein(1,1), Christoph Bamann(2,2), Egon Döberl(3), Dietmar Weinzinger(3), Wolfgang Promper(3), Tim Flohrer(4), Andrea Di Mira(4)

(1) German Aerospace Center (DLR), Institute of Technical Physics, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany, Email of corresponding author: stefan.scharring@dlr.de
(2) Technical University of Munich, Institute of Astronomical and Physical Geodesy, Arcisstr. 21, 80333 Munich, Germany.
(3) ASA Astrosysteme GmbH, Galgenau 19, 4212 Neumarkt im Mühlkreis, Austria
(4) European Space Agency – European Space Operations Center (ESA/ESOC), Robert-Bosch-Str. 5, 64293 Darmstadt, Germany

ABSTRACT

High-power lasers offer a unique potential for debris collision avoidance and orbit lowering for removal purposes within the debris mitigation scenario. Photon pressure and surface ablation are explored as suitable mechanisms to remotely apply the required velocity increment to debris targets. The appropriate regime of laser intensity and fluence, respectively, is discussed in terms of technical maturity and laser safety. Laser power beaming from ground to space is analysed considering atmospheric constraints like aerosol attenuation, cloud cover and turbulence including possibilities and limitations of technical counter-measures. Operational risks comprise uncertainties in momentum transfer as well as thermo-mechanical side effects highlighting the necessity of target reconnaissance. Moreover, making space debris touchable from ground might raise concerns of third parties regarding their own space assets not to be tackled by high-power lasers. Hence, the need for global governance of this approach for space debris mitigation is reflected.

1 INTRODUCTION

The large amount of space debris constitutes a high risk for space missions, in particular in the low Earth orbit (LEO) around 800 km altitude. Beyond residual objects from space missions like rocket bodies, inactive payloads or mission-related objects, a multitude of small fragments from explosions and collisions threatens active space missions. While fragments are difficult to be detected at object sizes on the order of few centimeters, they still may be lethal for active satellites due to the high relative velocities involved. Moreover, due to debris-debris collisions, an exponential increase of the debris population, referred to as the Kessler syndrome, might occur over the next decades.

In this paper, we discuss two different use cases for debris mitigation by ground-based high-power lasers: Collision avoidance and debris removal. As a near-term task, analysis of new collision avoidance technologies is fostered by the UN Guidelines on long-term sustainability [1]. As such a feasibility analysis, findings from our recent conceptual study named LARAMOTIONS (Laser Ranging and Momentum Transfer Systems Evolution Study) are presented which we have carried out for the European Space Agency [2]. There, we have analyzed the impact of laser photon pressure to a debris orbit. Even a deceleration by only $\Delta v = 1\,mm/s$ would yield an in-track displacement by more than 250 meters within 24 hours after laser operation [3] which is more than enough to avoid a collision in case that precise orbital data from the debris object are available. The great potential of laser-based momentum is that this way of collision avoidance would not only protect satellites, but even collisions between two different debris objects could be avoided, thus, eliminating a main driver of the current increase in the number of space debris objects.

The second use case for laser-based debris mitigation is addressed in the outer space treaty by the demand to ensure sustainable free exploration and usage of space by all nations [4]. In this regard, laser-based debris removal could mean to apply a large Δv to space debris. If we focus here on a large in-track Δv_t, approximately $\Delta v = 150 \dots 250\,m/s$ would be sufficient to initiate a Hohmann transfer that eventually yields atmospheric burn-up as can be computed from

[1] Present address: DLR, Institute of Space Systems, Robert-Hooke-Straße 7, 28359 Bremen, Germany
[2] Present address: Vyoma GmbH, Eckhardstraße 28, 64289 Darmstadt, Germany

Proc. 8th European Conference on Space Debris (virtual), Darmstadt, Germany, 20–23 April 2021, published by the ESA Space Debris Office
Ed. T. Flohrer, S. Lemmens & F. Schmitz, (http://conference.sdo.esoc.esa.int, May 2021)

$$\Delta v_t = \sqrt{\frac{G \cdot M}{R + z_0}} \left(1 - \sqrt{\frac{2R + 2z_1}{2R + z_0 + z_1}} \right) \quad (1)$$

where R and M are Earth's radius and mass, respectively, G the gravitational constant, z_0 is the initial debris altitude and z_1 is the targeted altitude for atmospheric burn-up ($z_1 \approx 50\ km$) or further drag-induced slowdown ($z_2 \approx 200\ km$). But as well radial Δv_r might be an option for success by lifting the apogee yielding perigee lowering as lined out in greater detail in [5].

With such a huge demand of debris velocity change, photon pressure is out of scope for debris removal, but laser ablation offers the potential to induce the required momentum remotely using high energy laser pulses – potentially suitable for collision avoidance as well. Whereas photon pressure was the only considered interaction mechanism in LARAMOTIONS, DLR's intrinsic work on laser-based orbit modification focuses on laser ablation. Hence, with the named study we take the opportunity to compare both approaches in detail.

Interestingly, photon pressure by continuously emitting (cw) lasers on a moderate output power level is frequently deemed a "civil" technology in opposite to "militarily" perceived laser ablation [3] which requires a high average (cw) or peak (pulsed) laser power.

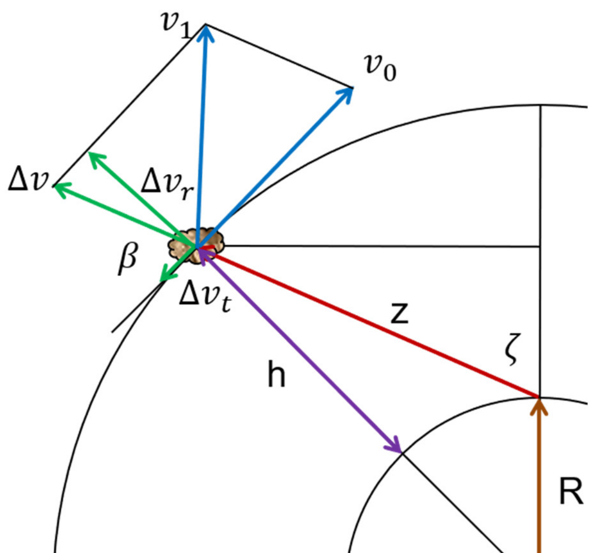

Figure 1. Schematic view on debris orbit modification using a ground-based high-power laser at the distance z from the debris orbit at an altitude h, not to scale. R: Earth's radius, a: orbit semi-major axis, ζ: zenith angle, v_0, v_1:velocity before and after laser engagement, resp.

Nevertheless, we have found that at those rather moderate power levels at which momentum transfer by photon pressure becomes efficient, high intensities at the target are required as well which are associated with significant thermal effects. Acknowledging that current laser weapon technology, albeit at a significantly higher power level, is typically based on cw, but not pulsed lasers. Therefore, we do not restrain our analysis to laser-induced momentum, but treat as well thermal effects to targeted debris for both laser-matter interaction mechanisms conceivable for laser-based debris mitigation.

2 THEORY OF LASER-INDUCED FORCES

2.1 Photon Pressure

Laser-induced force $\vec{F}$ from photon pressure depends on optical surface properties like absorptivity A, reflectivity (specular: R_S and diffuse R_D, resp.) and incident laser power P_L as given by [6]

$$\vec{F} = \frac{P_L}{c_0} \left[(A + R_D) \cdot \hat{k} - \left(\frac{R_D}{2} + 2 \cdot R_S \cos\vartheta \right) \hat{n} \right] \quad (2)$$

where c_0 denotes the propagation velocity of light in vacuum, $\hat{n}$ is the surface normal, $\hat{k}$ is the direction of the incident laser beam, and ϑ is the beam incidence angle. For the optical surface properties, the equation

$$R_A = R_S + R_D = 1 - A - T \quad (3)$$

holds where R_A is the albedo and T denotes the transmissivity. As a figure of merit, the momentum coupling coefficient of laser propulsion, $c_m = F/P_L = \Delta p/E_L$, denotes the ratio of force to incident laser power and momentum change to laser energy, respectively. For photon pressure c_m can amount up to 6.7 nN/W.

Not only laser-imparted momentum, but as well laser-induced heat Q should be considered for interaction with high-power lasers. It can be deduced from the object's absorptivity directly via $Q = \int A \cdot P_L dt$ and quantified by the coefficient of residual heat $\eta_{res} = \dot{Q}/P_L = Q/E_L$.

Finally, data on reflectivity can help to assess the risk arising from back-reflections at the debris surface. However, due to the large distances in space, the main threat that one could expect here would come from specular reflections at a very flat debris surface as, e.g., having occurred with the so-called Iridium flares.

In sum, laser-induced force by photon pressure as well as the accompanying phenomena of heat and back-reflections depend on material, laser wavelength λ and the debris' temperature. Disregarding thermal effects, all these quantities scale linearly with laser power.

2.2 Laser Ablation

Photon momentum is rather small when compared to a jet of propellant material. A short high energy laser pulse can create such a material jet in so-called laser ablation as a consequence of rapid material heating. In laser ablation, momentum coupling is between 3 and 5 orders of magnitude greater than with photon pressure, ranging from on to several hundreds of µN/W [7]. However, the ablation threshold fluence Φ_0 has to be exceeded which demands for large laser pulse energies since, e.g., for metals Φ_0 is in the range of $1 \dots 10\, J/cm^2$ if pulse durations τ in the nanosecond regime are used [8]. Of course, not only the ablated material is heated, but there can be as well a significant amount of thermal energy that remains at the debris object resulting in heat accumulation after several laser pulses [9].

The key parameter in laser ablation is the incident laser fluence Φ. However, predictability of heat and momentum induced to a debris target from ground is rather difficult, since the related fluence dependencies are strongly non-linear and pronounced dependencies on material as well as laser parameters λ and τ exist [7].

2.3 Atmospheric Laser Beam Propagation

In laser ablation high fluences are needed which require high energy as well as beam focusing to a small laser spot area in orbit. In many cases such a small spot is relevant for photon pressure as well in order not to lose laser power in outshining the debris target. Therefore, it is essential to choose a laser with a good beam quality M^2, i.e., M^2 close to 1 (diffraction-limited), and a laser transmitter with a large aperture. Theoretically, this allows to create a meter-sized laser focus in LEO for which the radius can be computed in the case of vacuum propagation as $w_f(z) = M^2 \lambda z / (\pi w_0)$ where w_0 is the initial beam radius and z denotes the distance between laser transmitter and debris target. However, fluctuations of the refractive index caused by atmospheric turbulence can dramatically increase the achievable focus spot size as can be seen from Fig. 2. Since this would prevent successful laser operations, the usage of adaptive optics as a countermeasure is mandatory for ground-based laser operation. For this purpose, wave-front analysis of light from a laser guide star would enable to anticipate the deformation of the laser beam. Then, in analogy to noise-cancelling headphones, actuators could be used to deform the transmitter optics in a complementary way that eventually can be quantified using the Strehl ratio Str yielding $w_f(z) = M^2 \lambda z / \left(\pi w_0 \sqrt{Str}\right)$.

On top of that, beam pointing jitter has to be considered as well as some uncertainty about the true debris position which is presumably monitored by laser tracking. Finally, there might be beam blocking or at least attenuation by atmospheric molecules, aerosols, and, in particular, clouds.

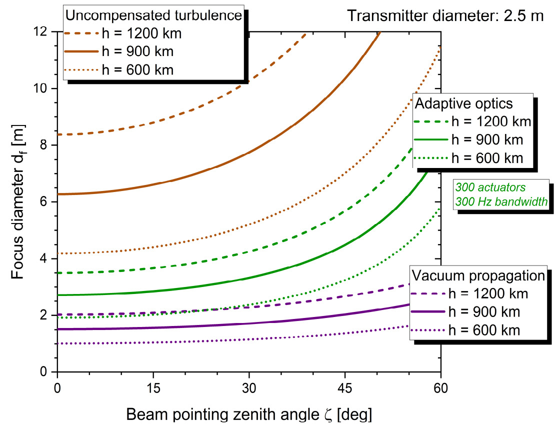

Figure 2. Laser spot diameter d_f at the debris position in the orbital altitude h for uncompensated atmospheric turbulence, turbulence compensation using adaptive optics and the theoretical case of vacuum propagation.

3 COMPUTATIONAL METHOD

3.1 Laser and Transmitter Configuration

In our feasibility study we employ high-power lasers in the near-infrared (NIR). From the beam propagation viewpoint, this is a trade-off between good focusability using a rather short wavelength and avoidance of light pollution as well as dazzling from scattered visible laser light. Suitable high-power lasers here are, e.g., solid-state fibre lasers, being commercially available with an average output power of $P_L = 10\ kW$ at a superior beam quality of $M^2 = 1.5$. Applying beam combining of two such high-power lasers and, in addition to that, anticipating a near-term scaling factor of 2, a laser power of at least 40 kW can realistically expected to be available for the future operation of ground-based lasers exerting photon pressure to space debris. As a very commonly used wavelength with solid-state lasers, $\lambda = 1064\ nm$ is assumed for the sake of simplicity.

Regarding high energy lasers for imparted momentum by laser ablation, we refer here to the beamlines of research facilities for inertial confinement fusion like the National Ignition Facility (NIF) at LLNL Livermore, California, USA or Laser Mégajoule near Bordeaux, France. The NIF laser beamlines, which can deliver a laser pulse energy > 19 kJ each at a wavelength of $\lambda = 1054\ nm$, exhibit a short pulse duration of $\tau = 5\ ns$ [10]. In our simulations we consider their rectangular beam profile by assuming a slightly enhanced beam quality parameter of $M^2 = 2.25$.

For laser beam transmission, we propose a telescope with a 2.5 m aperture diameter and consider a possible power loss of 2% in outshining. For the adaptive optics of the transmitter we assume 300 actuators with 300 Hz bandwidth, from which we derive the Strehl ratio that eventually yields the diameter of the laser focus shown in

Figure 2. For the beam propagation path through the atmosphere, a typical aerosol optical depth under clear atmospheric conditions has been calculated from [11].

3.2 Selection of Sample Debris Targets

For the analysis of laser-induced momentum and heat in photon pressure and laser ablation, we have chosen four different types of debris: rocket bodies (RB), payloads (PL), mission-related objects (MRO), and fragments (FG), cf. Tab.1. We have employed ESA's DISCOS database to pick some representative examples regarding mass, size, and area-to-mass ratio. Information on debris altitude has been taken from USSTRATCOM TLE data as of July 2, 2019.

Note that for fragments from explosions and collisions, we have additionally used ESA's MASTER model of the debris population and statistics from ground-based satellite crash tests to derive some estimates of the debris' properties.

Table 1. Orbit altitude h, mass m, characteristic length L_c and area-to-mass ratio of representative debris objects in LEO.

Type	#	Norad-ID	h $[km]$	m $[kg]$	L_c $[m]$	A/m $[m^2/kg]$
RB	a	19421	1111	23.8	1.15	0.026
RB	b	23279	937	1421	5.18	0.010
RB	c	22566	859	8226	8.23	0.005
PL	a	43018	649	1.0	0.10	0.015
PL	b	25478	799	42.0	2.38	0.076
PL	c	11326	983	802.8	2.07	0.006
MRO	a	37734	706	1.0	0.20	0.025
MRO	b	23250	737	5.0	0.80	0.071
MRO	c	33398	661	50.0	2.50	0.079
FG	a	42383	867	0.6	0.10	0.014
FG	b	33920	790	1.8	0.15	0.010
FG	c	33859	772	3.7	0.19	0.008

Following the findings from [12] we employ a debris albedo of $R_A = 0.12$ for integer targets and $R_A = 0.275$ for fragments, respectively, to compute the magnitude of both laser photon pressure as well as applied heat to the debris target. Concerning laser ablation, we have derived fit parameters for the empirical functions of $c_m(\Phi)$ and $\eta_{res}(\Phi)$ proposed in [13] to use the experimental data for c_m from [14] in laser ablation of aluminum and steel at the given laser parameters as well as corresponding simulation results of η_{res} from finite-element modeling as lined out in [15]. As a prevalent debris material, data for aluminum is used apart from rocket bodies where we assume steel as surface material.

In our simulations we discard any effects arising from tracking uncertainty or beam pointing jitter. Moreover, in accumulation debris cooldown due to heat radiation during the laser irradiation is neglected in a good approximation, cf. [9].

3.3 Computation of Target Deceleration

For all debris sample targets, we assume a circular orbit with the particular altitude h as given in Table 1. Moreover, a direct station transit through the zenith is simulated. The debris object is irradiated from 25° to 75° elevation. For the computation of laser-imparted deceleration by $\delta v_t(t)$ during the timestep δt we consider the focus spot area $A_f(h,\zeta)$, cf. Figure 2, which is compared with the optical cross-section A_{cs} of the debris. Then, in the case of target outshining, i.e., $A_{cs} < A_f(h,\zeta)$, the computed momentum is reduced according to $\delta v_t(h,\zeta) = A_{cs}/A_f(h,\zeta) \cdot \delta v_t(P_L)$ to consider the power losses due to the laser photons that miss the target.

4 SIMULATION RESULTS

4.1 Deceleration by Photon Pressure

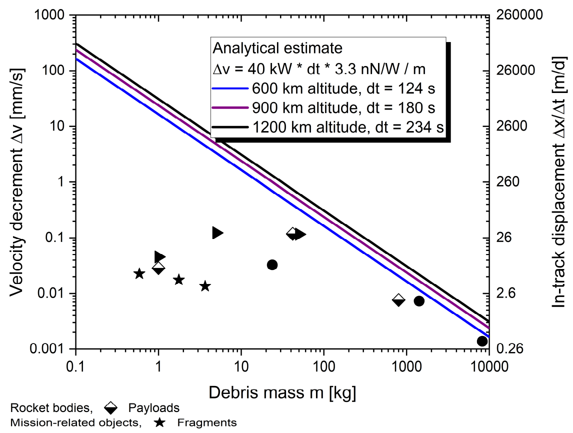

Figure 3. Simulation results for the velocity decrement from photon pressure debris irradiation by a laser station with $P_L = 40\ kW$ for the sample debris objects shown in Table 1. For the analytical estimate, see text, dt denotes the irradiation timeframe, given by $\zeta \in [15°; 65°]$, and $c_{m,0} = 3.3\ nN/W$ for an entirely absorptive object (A=1).

Except for the massive debris objects with $m > 800\ kg$ the achieved velocity change by photon pressure during a transit above a laser station with $P_L = 40\ kW$ is in the order of $\Delta v_t = 10 \ldots 200\ \mu m/s$ which at least effectuates an in-track displacement of some meters one day after laser irradiation. For collision avoidance, several subsequent laser irradiations would be required, preferably from a station network, as described in [16].

For debris objects with $m > 40\,kg$ the reciprocal dependency $\Delta v \propto m^{-1}$ that can be expected from the definition of momentum coupling, $c_m E_L = m \cdot \Delta v$, cf. Sect. 2.1, is clearly reproduced in Figure 3. Moreover, the deviation of the simulation results from the analytical estimate using $\Delta v = P_L \cdot dt \cdot c_{m,0}/m$ in particular reflect the fraction of velocity change $v_t(t)/\Delta v(t)$ that can be used for in-track deceleration, cf. Figure 1.

The reason for the underperformance of momentum transfer for the lightweight targets can be found in the still relatively large laser beam diameter compared to their characteristic length of $L_c < 2\,m$. In this regard, the stagnation in the increase of velocity decrement when going to smaller masses is an indicator of large outshining losses for small debris. Nevertheless, it should be considered that in the case of debris-vs.-debris collisions the ability for collision avoidance can be extended by irradiating both objects, e.g., decelerating the "chaser" of the conjunction partners and accelerating the "target" [16].

Other options to obtain a large deceleration are the usage of a multitude of laser station passes or an increase of laser power, if available.

4.2 Deceleration by Laser Ablation

As an alternative that might constitute a more efficient way for collision avoidance, the usage of laser ablation as an interaction mechanism has been investigated.

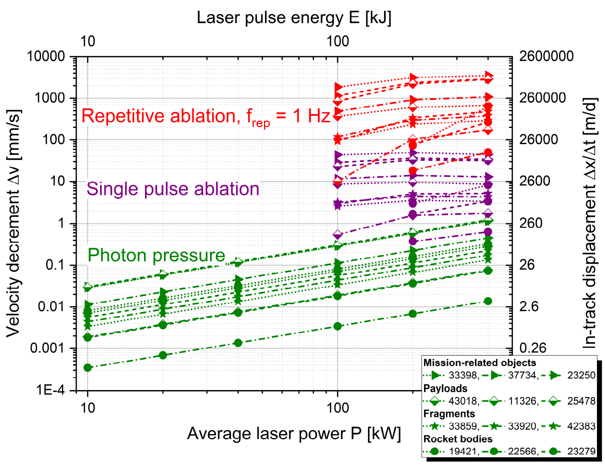

Figure 4. Comparison of simulation results for velocity decrement from photon pressure and repetitive laser ablation during a high-power laser station transit. Moreover, the possible outcome of a collision manoeuvre consisting of a single *laser pulse is shown.*

In our simulations we have found that if the laser pulse energy is too low, the debris trajectory will not change at all, since the threshold fluence for laser ablation, which is in the range of $\Phi_0 = 1 \ldots 2\ J/cm^2$, is not exceeded yet. Instead, more than $E_L = 50\ kJ$ laser pulse energy would be required in order to cause laser ablation at the surface of the employed debris' materials. It is important to note here that this can only constitute a very preliminary assessment of the required laser pulse energy, since other materials exhibit different ablation thresholds, and other laser configurations in terms of λ and τ do change the picture as well. Finally, we have assumed a top hat beam profile in orbit whereas the real fluence distribution will rather resemble a Gaussian of which the peak fluence exceeds the average fluence in a top hat profile by a factor of 2. In this regard, we have shown in a more sophisticated numerical analysis, that already beam combining of 2 NIF laser beamlines might be sufficient to yield ablation and successful collision avoidance [17].

If, however, now Φ_0 is exceeded in the laser focus spot at the debris' position, collision avoidance can be undertaken instantaneously within a single laser pulse, in contrast to photon pressure, which requires several station transits. Admittedly, this is no straightforward technology solution since laser technology yielding such a large pulse energy is not available commercially of the shelf but can only be found at a few research facilities, cf. Sect. 3.1. Such laser beamlines could for example be achieved by beam combining of several laser beamlines as used for inertial confinement fusion. In principle, one could also operate several of those combined beamlines subsequently after each other, for example with a pulse repetition rate of 1 Hz. Then, at the same average laser power as for photon pressure, momentum coupling would be three to four orders of magnitude higher using laser ablation, cf. Figure 4, eventually yielding a velocity decrement in the order of m/s. Hence, it is conceivable that, after a multitude of transits above such a laser station, the overall deceleration will yield perigee lowering being sufficient for debris removal by atmospheric burnup.

4.3 Laser-induced Debris Heating

If too much heat is acquired by the debris target during laser operation one might run the risk of target meltdown or droplet formation [9]. Heat accumulation has to be assessed carefully to avoid fragmentation from thermal stress [18], e.g., in solar panel fragments, or detonation of stored energy, e.g., in residual amounts of propellant or incompletely discharged batteries. It is obvious that for collision avoidance the usage of a single laser pulse instead of irradiation during several minutes is likely to be beneficial in terms of heat accumulation, but the risk of fragmentation due to shockwaves has to be assessed for laser ablation in general. Therefore, the risk assessment of target heating is the most complex in the case of repetitive ablation for debris removal and requires dedicated target reconnaissance.

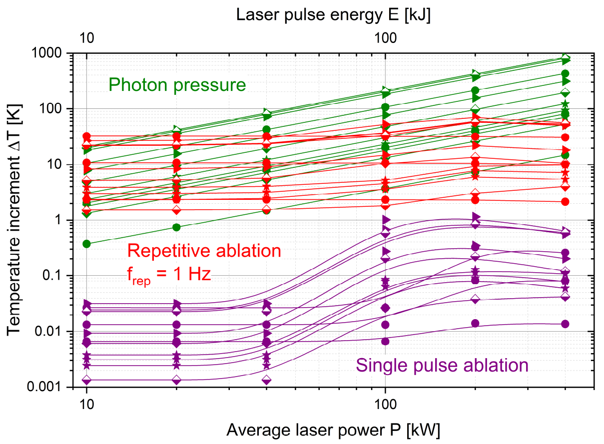

Figure 5. Simulation results for temperature increase by laser heating during a laser-based orbit modification manoeuvre. For legend cf. Fig. 4.

5 DISCUSSION

From an astrodynamics viewpoint, laser-induced orbit modification from ground appears as an attractive approach for space debris mitigation. Reviewing, however, the findings from our simulations considering operational safety, several concerns have to be addressed in order to avoid that such operations turn out a harmful activity in the light of [19]. The lasers are operated here on a power level which is some orders of magnitude beyond the maximum permissible exposure for the human eye which in particular has to be regarded in safety measures for air traffic and the public on ground. Moreover, the risk of accidental illumination of active satellites in the foreground or background of the debris target has to be ruled out carefully [1]. Moreover, laser-induced heat shall not endanger the target integrity as addressed by Sect. B.10 of [1]. In addition to that, momentum uncertainties that can arise, e.g., from insufficient target reconnaissance as well as from pointing jitter of the high-power beam or the residual position uncertainty from laser tracking data, have to be considered before giving clearance for orbit modification.

Considering the high level of intensity and fluence, respectively, which is required for substantial orbit modification, the employed technology can to a great extent be considered dual use [20], regardless whether cw or pulsed lasers are employed. In particular since it constitutes a potential means for active debris removal, the risk of weaponization [21] should be addressed by searching ways for global governance for the peaceful usage of high-power lasers in space [22].

6 CONCLUSIONS AND OUTLOOK

Laser-based orbit modification has the potential of ground-based access to a multitude of space debris objects. Photon pressure is rather a near-term option using commercially available lasers, but it has the drawback of very small forces suitable rather for collision avoidance only. Laser ablation is much more powerful, exhibits a better ratio of residual heat to applied momentum but it is much more complicated to predict. The most crucial technological challenges here might be turbulence compensation for high intensity power beaming and debris reconnaissance for the assessment of thermal integrity. High-power laser usage requires to carefully address several operational risks, ranging from unintended dazzling to the threat of weaponization.

The successful implementation of such a normative framework bears the potential to tackle the global problem of space debris pollution by a joint, global initiative. Though serious concerns of operational safety lined out in this paper – collateral collisions, thermal damage, and laser back-reflections – pose a remarkable challenge on this path, the threating scenario of a possible exponential and irreversible increase of space debris pollution in LEO renders those technological challenges worth to be addressed for sustainable space operations.

High-power laser technology offers a unique potential to contribute to space debris mitigation on a grand scale. Therefore, joint efforts should be undertaken to exploit this field of laser applications in a beneficial way and to make its implementation less futuristic than the onset of an exponential evolution of space debris itself.

7 ACKNOWLEDGMENTS

Funding by the European Space Agency for research on collision avoidance using laser photon pressure under contract No. 4000127148/19/D/CT is gratefully acknowledged as well as DLR-TP's institutional funding for research on laser-ablative orbit modification.

The access to the USSTRATCOM catalogue of TLE data, the ESA DISCOS database as well as ESA's MASTER-8 debris population model is thankfully appreciated.

8 REFERENCES

1. UN Committee on the Peaceful Uses of Outer Space (2019). Guidelines for the long-term sustainability of outer space activities, A/AC.105/C.1/L.366.

2. Scharring, S. et al. (2021). Conceptual Study on Laser Networks for Near-term Collision Avoidance for Space Debris in the Low Earth Orbit, In *2021 International High Power Laser Ablation Symposium*, Santa Fe, NM, USA (virtual conference).

3. Mason, J. et al. (2011). Orbital debris-debris collision avoidance, *Adv. Space Res.* **48**, 1643-1655.

4. UN Office for Outer Space Affairs (1966). Treaty on Principles Governing the Activities of States in the

Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, United Nations.

5. Phipps, C.R. et al. (2012). Removing orbital debris with lasers, *Adv. Space Res.* **49**, 1283-1300.

6. Liedahl, D. et al. (2013). Pulsed laser interactions with space debris: Target shape effects, *Adv. Space Res.* **52**, 895-915.

7. Phipps, C. et al. (2010). Review: Laser-Ablation Propulsion, J. Propul. Power **26**(4), 609-637.

8. Bäuerle, D. (2011). *Laser Processing and Chemistry*, 4th ed., Springer, Heidelberg, Germany, p. 253.

9. Scharring, S., Lorbeer, R.-A. & Eckel, H.-A. (2018). Heat Accumulation in Laser-Based Removal of Space Debris, *AIAA J.* **56**(6), 2506-2508.

10. Haynam, C.A. et al. (2007). National Ignition Facility laser performance status, *Appl. Opt.* **46**(16), 3276-3303.

11. McClatchey, R.A. et al. (1972). *Optical properties of the atmosphere*, U.S. Air Force Research Laboratories.

12. Mulrooney, M.K. et al. (2008). An investigation of global albedo values. In *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*, pp. 17-19.

13. Scharring, S. et al. (2018). Momentum predictability and heat accumulation in laser-based space debris removal, *Opt. Eng.* **58**(1), 011004.

14. D'Souza, B.C. (2007). *Development of Impulse Measurement Techniques for the Investigation of Transient Forces due to Laser-induced Ablation*, PhD thesis, University of Southern California, USA.

15. Klein, E.M. (2021). *Simulation of Space Debris Heating in Laser-Ablative Orbit Modification Manouvers*, Master Thesis, Technical University of Braunschweig, Germany.

16. Dreyer, H. et al. (2021). Future improvements in conjunction assessment and collision avoidance using a combined laser tracking/nudging network. In *8th European Conference on Space Debris*, European Space Operations Center, Darmstadt, Germany (virtual conference).

17. Scharring, S. et al. (2021). *Ablative collision avoidance for space debris in the Lower Earth Orbit by a single multi-kJ pulse from a ground-based laser*, proposed for AMOS conference.

18. Loktionov, E., Phipps, C. & Sharaborova, E. (2021). Unintended consequences with laser nudging or re-entry of satellites, Acta Astronaut. **181**, 439-444.

19. UN Office for Outer Space Affairs (2010). *Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space*, United Nations.

20. European Parliament (2015). Commision delegated regulation EU 2015/2420 amending Council Regulation (EC) 428/2009 setting up a Community regime for the control of exports, transfer, brokering and transit of dual-use items, *Official Journal of the European Union*, L 340/1-301.

21. Dobos, B. & Prazak, J. (2019). To Clear or to Eliminate? Active Debris Removal Systems as Antisatellite Weapons, *Space Policy* **47**, 217-223.

22. Schmidt, N. & Ditrych, O. (2019). *Kick-starting Cosmopolitan Governance through Science: The Case of a Giant Laser System*, Policy Paper, Institute of International Relations, Prague, Czech Republic.