ORBITAL RE-FOCUSING OF HIGH ENERGY LASER BEAMS FROM GROUND FOR LASER-ABLATIVE POST-MISSION DISPOSAL AND DEBRIS REMOVAL

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ABSTRACT

Ground-based laser power beaming enables propulsion solutions for post-mission disposal (PMD) and active debris removal (ADR). In our conceptual study we find that the demand for large laser pulse energies (~100 kJ in ADR) can dramatically be lowered if the laser beam is re-focused in orbit, enabling the usage of currently available laser technology.

For PMD beam re-focusing onboard a satellite would power its laser-ablative propulsion unit. With 29 J pulses at 580 Hz repetition rate and less than 2 kg of propellant, the perigee of a small satellite at 600 km altitude could sufficiently be lowered within two years.

For ADR a relay satellite would divert 400 J laser pulses and focus them over up to 40 km distance. Regarding 10k debris objects and a beam relay at 550 km altitude, debris irradiation in a triple conjunction of ground station, relay, and debris is possible several times per day.

1 INTRODUCTION

Space debris mitigation and remediation are not just an internal issue of the space-related communities in the scientific, commercial, and military sectors of society. Rather renders the already existing interconnectedness of space activities with terrestrial infrastructure and, moreover, their far-ranging potential of future applications them a supportive tool and responsibility [1] for the establishment of the 17 global so-called Sustainability Development Goals as agreed upon within the Agenda 2030 of the United Nations [2]. In particular, the “establishment of new frameworks for space traffic, space debris and space resources” is explicitly agreed upon and demanded for “the exploration and use of outer space for peaceful purposes and for the benefit of all humanity” as one of the 56 actions of the United Nations’ Pact for the Future [3].

Given this social mandate, responsible behaviour in space is necessary, especially since a possible onset of an exponential growth of the space debris population, commonly referred to as the Kessler Syndrome [4], has already been observed in the Low Earth Orbit (LEO) regime at altitudes around the highly frequented sun-synchronous orbits (SSO) recently [5] and can clearly be predicted to massively occur throughout LEO from extrapolation of the current state of space traffic and debris environment into the upcoming decades [6].

However, not a single piece of space debris has actively been removed yet. In addition to that, adherence to the post-mission clearance of satellites and their related rocket bodies from LEO is still below 75% [6] of all objects that do not naturally decay within the agreed timespan of 25 years [7]. Moreover, much shorter timespans for PMD have already been proposed [8]. Together with the legacy of accumulated leftovers of long-ago missions, this enforces the increasing space traffic in LEO to navigate through a rising number of unwanted “graveyard orbits”, as such only foreseen beyond the geosynchronous orbit (GEO) – not to mention the numerous debris fragments, most of them too small to be permanently catalogued, but, in terms of mission operations, being “lethal, non-trackable” (LNT).

Post-mission disposal (PMD) maneuvers constitute extra effort in mission design in terms additional propulsion devices and/or propellant mass. In our work, we propose a simple satellite propulsion unit which benefits from its ability to be powered remotely from ground by laser radiation. Once power supply by a network of laser ground stations was provided, such laser PMD device might turn out as an attractive and cost-effective means to ensure a satellite’s ability for PMD within a rather short time span.

Regards the remediation of debris fragments, the frequently proposed usage of high-power lasers for remotely induced de-orbit has recently been highlighted by the U.S. National Aeronautics and Space Administration (NASA) in terms of its promising medium-term cost-benefit ratio [9]. Nevertheless, the technical hurdles to be overcome to establish an efficient laser system for active debris removal (ADR) are challenging as the laser fluences to achieve meaningful laser-ablative thrust require large pulse energies. Therefore, in order to benefit from the conceptual advantages of ground-based power beaming, we propose to re-focus the laser beam at a dedicated relay satellite which directly targets space debris in its vicinity.

The technological concepts and related mission scenarios of laser-based, remotely powered PMD and relay-assisted ADR are outlined and discussed in the following at the background of preceding research and developments in the field of laser propulsion.

2 LASER PROPULSION CONCEPTS

Concepts for laser-based propulsion have been discussed since the early 1970's [10], soon after the invention of the laser itself in 1960. The coherence of laser light, i.e., the equality in wavelength, phase and direction of the emitted photons, enables beam focusing over large distances to a very small focal spot. Thus, power beaming using directed laser energy exhib0its an intriguing potential for space propulsion concepts to increase the specific impulse of a propulsion system tremendously or even, in the case of propellantless air-breathing laser propulsion, indefinitely.

Moreover, the generation of relatively short (down to nanoseconds) and even ultra-short (pico- and femtoseconds) laser pulses opened up the field of laser-based ablation of a target's surface material due to rapid and confined energy absorption from an intense laser pulse. Beyond various applications in material processing material ablation soon proved [11] as a source of considerable recoil from the exhaust jet exerted on the irradiated target, quantified by the momentum coupling coefficient $c_m = \Delta p / E_L$ as the ratio of imparted momentum Δp to laser pulse energy E_L, opening up the multifaceted field of laser-ablative propulsion [12].

2.1 Remotely-powered Propulsion

Breaking the barriers of specific impulse applicable in chemical propulsion as well as overcoming the resource constraints of power supply in electric propulsion, remotely-based laser propulsion might be regarded as a disruptive technological concept for space propulsion in general, showing sort of similarity to the ground-breaking transition from steam trains to remote power supply by overhead wiring in the 19th century.

Similarly, innovative concepts and experimental studies for launchers of smaller satellites arose making use of laser radiation by a heat exchanger [14], a chamber for laser-induced detonation [15] and/or a propellant supply for material ablation [16].

At the other end of possible space applications, even the idea of interstellar propulsion using photon pressure is intensely pursued in the so-called Breakthrough Starshot project aiming to send a light-weight probe to α-Centauri [17].

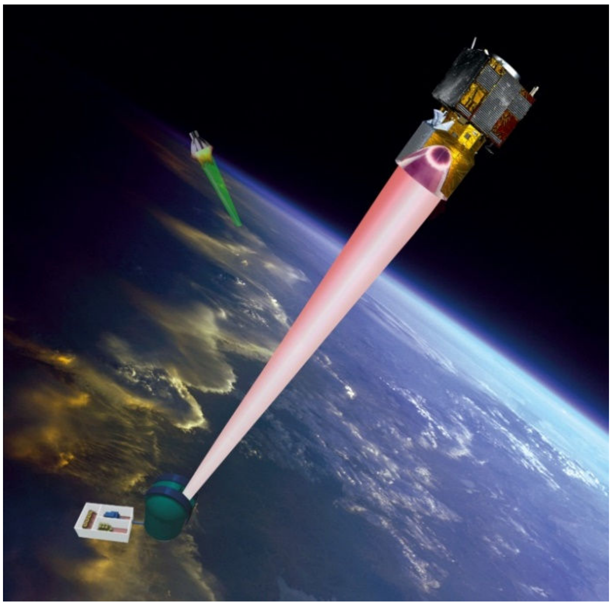

Figure 1. Artist impression of a nanosat launch using a high-energy laser ground station with power beaming to the satellite's propulsion unit for thrust generation by material ablation and plasma detonation. Image: DLR.

The mentioned concepts uniquely rely on splitting the propulsion mechanism into a complex ground infrastructure and a relatively simple propulsion device, cf. Fig. 1. The large distance between both components, however, demands a good beam quality for focusing. In this regard, the availability of suitable lasers is currently limited to an average optical power below 100 kW. A satellite's launch to LEO, however, would require 1 MW laser power per kilogram payload mass [18] while for the ambitious Breakthrough Starshot endeavour even an overall laser power of 100 GW would be needed [17].

2.2 Laser-Propelled Space Debris

In the field of space debris mitigation, concepts employing ground-based [19] or space-based lasers [20] emerged in the 1990's, since remotely induced momentum transfer appeared as well as a promising approach to address the vast multitude of debris fragments which cannot be tackled by specific in-space missions.

Though space debris can be considered an "uncooperative" target for propulsion attempts, laser-ablative momentum can be generated at literally every kind of material of any object shape as long as light of the particular laser wavelength is intensely absorbed [21,22]. Moreover, in contrast to launcher concepts, the long-term goal of debris deceleration for eventual atmospheric burn-up does not imply any requirements on minimum laser power. Instead, debris pieces can be decelerated (impulse)bit-wise during several laser engagements, cf. Fig. 2.

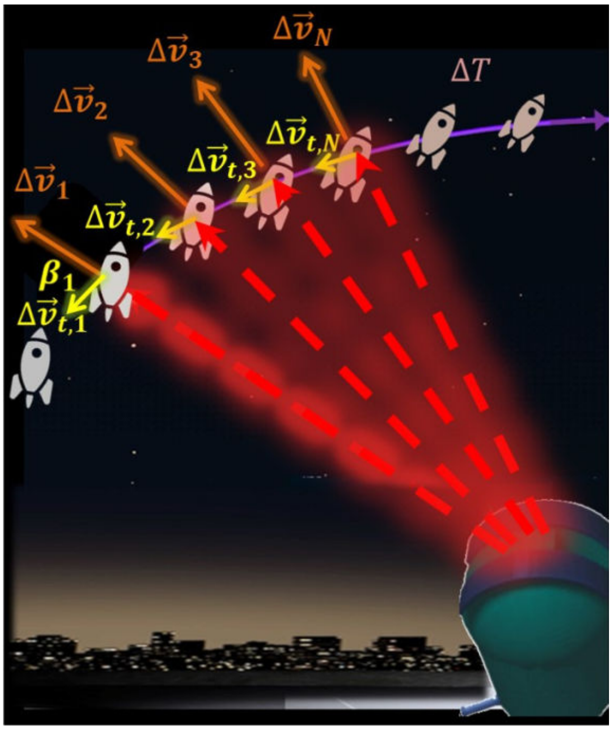

Figure 2. Scheme of remotely-induced laser-ablative deceleration of space debris for removal by atmospheric burn-up (from [23] under CC BY 4.0 license).

At present, however, space debris removal by a remotely-powered laser-ablative propulsion mechanism is impeded by the required large laser pulse energies: with a laser ablation threshold fluence of a few J/cm² and an orbital laser spot size of a few meters for ground-based lasers, the resulting laser pulse energy is in the order of 100 kJ for a reasonable transmitter layout [23] – which is far beyond commercially available lasers (around 10 J) and even greater than the largest existing single beamlines (19 kJ [24]). Technological options for coherent beam combining of several laser beams exist, however, like in the field of laser launchers, are not proven yet for the required massive laser power scaling. Nevertheless, incoherent beam combining using multiple laser facilities aiming to the same object could still be an option to achieve the required fluence.

2.3 On-board Laser Propulsion

Facing the current laser power limitations, on-board laser propulsion in micro propulsion devices for attitude and orbit control (AOCS) using commercially available lasers became an emerging field of interest in the early 2000's. As space qualification of such lasers constitutes a remarkable development effort, only moderate laser powers up to a few W were envisaged enabling thrust in the µN to mN range, however, with a remarkable impulse bit resolution in the order of down to even tens of pNs [25,26].

Advanced laser micro thruster concepts comprised electro-optical beam steering for ultrafine positioning due to extremely low thrust noise [27], and a first in-orbit demonstration of attitude control using laser micro propulsion has been performed recently [28].

3 POST-MISSION DISPOSAL

The thrust limitations of a laser-ablative propulsion unit onboard a satellite due to the required ability of the laser for space operations can be overcome if the onboard laser is replaced by a high-power laser ground station which is used for energy transmission to the satellite. Re-focusing of the incoming beam on-board the satellite would then allow for the generation of considerably larger thrust making a laser-ablative propulsion unit suitable for post-mission disposal, which is explored in the following.

3.1 Technological Concept

To verify the feasibility of an on-board laser fluence concentrator we simulated the performance of an optical focussing system using raytracing (Zemax OpticStudio version 19.8).

This allows to generate two-dimensional fluence maps, which we use to calculate the distribution of impulse, mass removal and the jet efficiency based on simulated laser-matter interaction data for aluminium taken from [29].

A representative set of parameters was chosen, which could be reproduced in the laboratory to allow for experimental verification. This leads to the choice of a rather small aperture of 100 mm for this first iteration. Future systems will most likely have a larger overall aperture. The laser radiation is expected to outshine the optical element. To minimize weight and complexity regarding its future space operation, a reflective optic using a spherical concave mirror (curvature radius: 400 mm) was selected.

To move the mirror out of the ablated material beam, it needs to be tilted and focus the radiation to a target ablator right next to it. Additional optics may be deployed to shield the concentrator from the ablated material plume. Nevertheless, these optics were not accounted for in our simulations since that would lead to additional aberrations. The variation of the angle between the direction of incidence at the collecting mirror and the direction of the reflected beam to 0°, 5°, 10°, 15° and 20°

allows to analyse this effect on the thrust in greater detail.

To achieve significant fluences on the propellant surface, we assumed a pulse energy of 50 J which corresponds to approximately 0.6 J/cm² at the receiver aperture.

As a second parameter the distance of the ablation target from the expected focal plane was varied to analyze the relevance of refocussing optics with respect to the increasing depth of the propellant target.

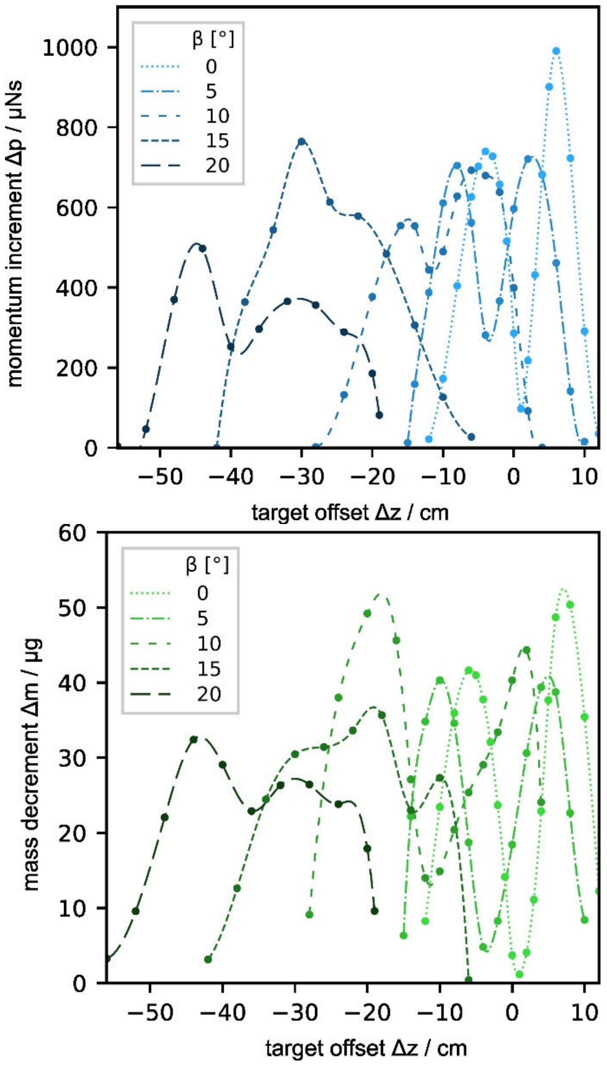

Figure 3. Results for a concave mirror as concentrator at $\Delta z' = 20$ cm. Impulse bit Δp (top) and removed mass Δm_{abl} (bottom) per pulse with respect to the angle of reflection and distance delta z relative to the focal plane. Dashed lines are for improved visibility only and do not resemble a model.

As a reference for $\beta = 0°$ the typical focal effect of a concave mirror is shown by the dotted lines in Fig. 3. Here, three relevant observations can be made. First, by defocusing the system far enough, the ablation effect fades away and all parameters tend to zero. Second, close to the focal plane there is a strong indent for all parameters. This stems from the vast increase in fluence at the focal point significantly past optimal parameters. This typically leads to very high plasma temperatures and a large specific impulse, but yields only a low amount of thrust. Therefore, significant thrust can be generated even at significantly reduced incidence fluences, if optomechanical properties can be controlled with sufficient accuracy (e.g. $\Delta z < 1$ cm at $\beta < 5°$). Third, there is an asymmetry with respect to the focal position above and below the focal point. This is most likely caused by the spherical aberrations introduced by the spherical mirror, which translate to an asymmetry of the fluence distribution with respect to the optical axis.

Considering oblique laser incidence, it can be seen for $\beta = 15°$ that, although the aberrations increased significantly, the system is able to generate results similar or even on par with the reference case of $\beta = 0°$, even though at a significantly increased distance. Nevertheless, at $\beta = 20°$ all metrics degrade for all distances evaluated.

Overall, we find that the system performance becomes very robust against misalignment and system aberrations for multiple optical concepts at a pulse energy of 50 J. A more detailed analysis, however, revealed that the system would already become operational at an incident pulse energy of only 10 J. A conceptual draft of such a laser-ablative propulsion system is shown in Fig. 4.

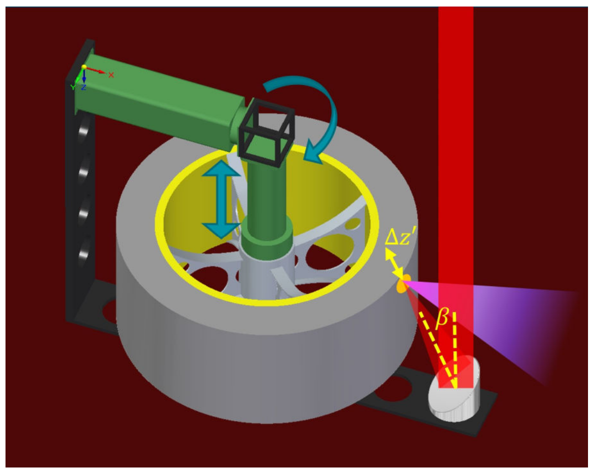

Figure 4. Laser-ablative propulsion unit with a concave mirror focusing the incoming laser beam onto a rod of propellant material. Homogeneous surface ablation is provided using translational as well as rotational actuators. Image: DLR

These results allow for an outlook on the applicability of concentrators for laser ablative propulsion.

Obviously an in-orbit system should exhibit a greater aperture diameter and should be optimized for the applied incidence angle. This would greatly reduce the degrading effect induced by the tilting of the optic. Nevertheless, the results indicate, that for sufficiently large fluences the surface, tilt and position tolerances allowed for the optical concentrators may become quite large. Therefore, it is desirable to verify these results experimentally and to perform a virtual optimization of multiple optical concentrators designed specifically for the mission and ground station constraints.

This includes the evaluation of transmissive optics, like lenses, Fresnel-lenses or diffractive optical elements as well as on-board optics, which were used during the main mission and now can be repurposed for the end-of-life procedure.

3.2 Mission Scenario

The concept of a laser-powered post-mission maneuver is depicted in Fig. 5: A satellite at the end-of-life on a circular LEO orbit (green) receives high energy laser pulses transmitted from ground during multiple station overpasses. The laser pulses are directed onboard the satellite into the laser propulsion unit, where impulse bits are generated by recoil from propellant surface ablation. The overall velocity decrement Δv_{laser} from each laser engagement during an overpass yields further lowering of the orbits' perigee, constituting a series of Hohmann transfer maneuvers in an optimal case, indicated by the red trajectories. Once the perigee has decreased sufficiently, down to approximately 250 km, the orbit's apogee is reduced step-by-step in a second, passive PMD phase due to atmospheric drag around the perigee (blue trajectories). Finally, when the orbit has circularized and the satellite experiences drag from residual atmosphere throughout its orbit, either an uncontrolled re-entry by continuous drag-induced deceleration can be envisaged or, alternatively, ground-based supply of laser energy can be employed again for a short laser-ablative high-impulse maneuver to achieve controlled de-orbit (yellow trajectory) from approximately 180 km perigee altitude down 50 km for immediate demise.

To assess the feasibility of laser-assisted PMD, an algorithm for end-to-end simulation was developed [30] and patented [31]. For its implementation the General Mission Analysis Tool (GMAT) [32] by NASA was employed. The simulations comprised 1. configuration of laser ground station and transmitter, 2. prediction of contact times during station overpasses, 3. beam propagation including extinction and turbulence compensation, 4. analysis of momentum, heat and propellant consumption during laser-ablative propulsion phases, and 5. orbit propagation for the assessment of PMD duration.

PMD from three different initial circular orbits (600, 900, and 1200 km altitude) using a single ground station was analysed for three different satellite masses each (150, 850, 1500 kg). A high-power laser with a single pulse energy of 29 J and 1 ns pulse duration at 1064 nm wavelength was assumed together with a 2.5 m aperture transmitter. The satellite's propulsion was fed by the incoming laser beam, focused by a 1.5 m aperture receiver onto a small spot of 1.2 cm diameter on the aluminium propellant supply. The mission duration requirements were set 2 years for active perigee lowering in phase 1 and a single station transit for controlled de-orbit in phase 3. For the latter, mostly larger pulse energies and spot sizes were employed in order to keep the time between two pulses large enough to avoid pre-pulse shielding above the propellant surface.

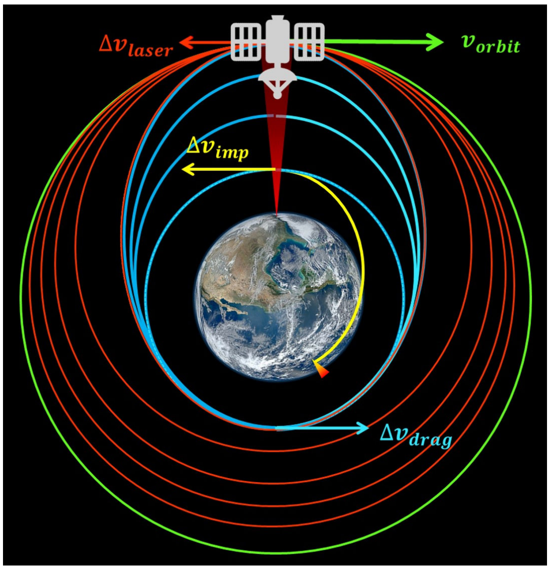

Figure 5. Phases of laser-powered post-mission disposal of satellite with receiver unit and laser propulsion module: 1. Laser-powered perigee lowering (red), 2. Drag-induced apogee decrease (blue), 3. High-impulse controlled de-orbit (yellow), if needed. Image: DLR

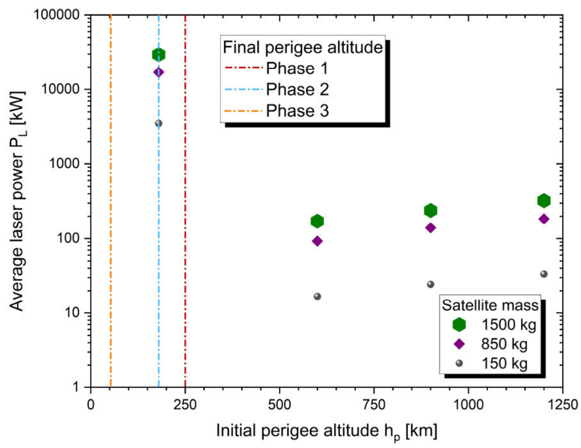

Figure 6. Average laser power requirements for laser-driven phases of post-mission disposal for different satellite masses. Data for perigee altitudes above 500 km refer to phase 1 (laser-powered perigee lowering) while values for 180 km represent the initial altitude of phase 3 (controlled de-orbit).

It can be taken from the simulation results depicted in Fig. 6 that for a controlled re-entry, the phase 3 requirement of a high impulse maneuver during a single station overpass implies a huge demand of average laser power of a few MW and more, which likely cannot be met in foreseeable future for pulsed lasers at high pulse energies and high repetition rates.

Regarding phase 1, however, we found that single-ground-station laser-powered perigee lowering from a LEO within two years for uncontrolled re-entry appears to be feasible. While for medium and large satellites still a very high laser power around 100 to 300 kW would be needed, the laser power requirements of less than 40 kW for a small satellite of 150 kg mass are within in the realm of conceivable mid-term developments. In particular, it would require an average laser power of approximately only 17 kW (29 J pulse energy at 580 Hz repetition rate) to lower the perigee of a small satellite from 600 km altitude sufficiently using less than 2 kg of aluminium propellant for ablation. Note that the structural mass of the laser receiver and propulsion unit has been discarded in this simulation. However, as a rough estimate we assume that it would amount to only approximately half of the mass of a comparable Hall- or Ion thruster.

Overall, the related laser configuration is well conceivable in terms of current research and development, cf. the estimate below in Sect. 4.1.

4 ACTIVE DEBRIS REMOVAL

As we have shown for laser PMD that re-focusing of laser radiation from ground allows to induce laser ablation by rather low initial laser pulse energies, we explore in the following to extend this approach to laser-driven removal of space debris fragments, which enhances the number of the involved, spatially separated entities from two to three, namely the laser ground station, a re-focusing relay satellite, and the space debris target. While this adds to technological complexity, the required laser pulse energy could be dramatically lowered down to a realistic level enabling near-term implementation and testing.

4.1 Technological Concept

The concept of beam relay was introduced and tested by the U.S. Strategic Defense Initiative Organization (SDIO) in the 90' [28,34]. In the experiment, the beam was relayed from laser ground station to a satellite at 450 km altitude and back to a target scoring site on ground nearby. If, in our case of space debris remediation, the beam was relayed from the satellite to a space debris object, cf. Fig. 7, the distance from the focusing element would be significantly shorter and the focal spot smaller than achievable over large distances, thus requiring significantly less energy to exceed the ablation threshold than in the case of direct power beaming from ground to the debris.

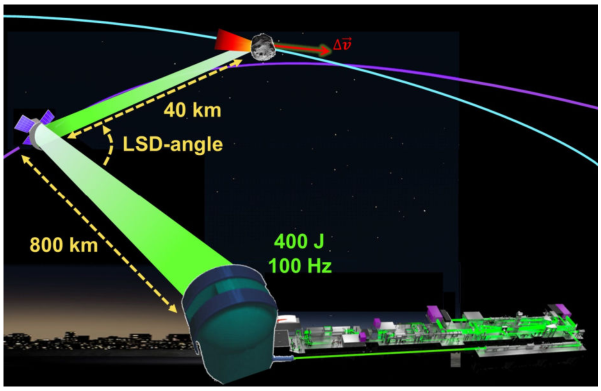

Figure 7. Space debris irradiation using relay-mirror (Image: HiLase / DLR).

For example, if the distance between a relay satellite and the debris would be around 40 km, then by using a focusing mirror with 2 m diameter (diffraction limit diameter 3.7 cm), the fluence of 10 J/cm^2 in the centre of the beam can be reached with 100 times less pulse energy in comparison with a ground system using a 4 m diameter focusing mirror over a focusing distance of 800 km (diffraction limit diameter 37 cm), as proposed in [35]. If atmospheric losses and turbulences are neglected, the ground system would need around 5 kJ of energy to reach the ablation, while the relayed beam concept would need only around 50 J of energy. To account for air turbulences and atmospheric attenuation, the ground system proposed in [35] employs a 25-kJ laser operating at 10 Hz. Due to the large spot in orbit in directly focusing from ground and the related outshining of comparatively small debris fragments, such a 25-kJ laser would deliver, e.g., only 7% of energy at a debris object of 10 cm diameter (less if beam degrades during the atmospheric propagation). However, the same energy (and comparable thrust) can be delivered by a 190 J laser within 10 pulses when a beam relay is used instead.

Since the relayed laser uses the full Gaussian profile on target, the fluence and also the thrust varies along the beam, the required energy or repetition rate will be higher. We considered margin up to 100 %, so eventually the energy of the laser could go up to 400 J with a repetition rate of 100 Hz or the repetition rate could go up to 200 Hz with the energy of 200 J. Recently, the CLF STFC UK (Central Laser Facility, Science and Technology Facilities Council) in joint project with HiLASE developed a 150 J laser operating at 10 Hz [36] as well as a 10 J laser operating at 100 Hz [37]. The 100 Hz system operates under the same fluence as the 10 Hz system, but the heat density is 10 times higher, therefore its technically feasible to increase the repetition rate to 100 Hz at an energy of 100 J. By using the largest Yb:YAG (ytterbium-doped yttrium aluminum garnet) slabs currently available, it's possible to achieve energy of 400 J yielding an overall average power of 40 kW.

With a smaller beam spot, laser pointing and target tracking will be more critical in comparison with operation of the widely outshining 25-kJ laser from ground. However, as modern laser directed energy weapons claim to hit 2 cm non-cooperative target at km distance [38], successful target engagement should also be feasible technically. Moreover, detailed concepts for debris detection, tracking and power beaming from orbit have already been elaborated in conceptual studies on space-borne laser-ablative debris removal, cf., e.g. [39], and might be adapted correspondingly for a beam relay satellite.

4.2 Mission Scenario

During the mission, the ground laser, located in the Czech Republic, would fire onto a relay satellite reflecting and focusing the beam to a space debris object as pictured in Fig. 7.

To demonstrate the feasibility of this approach, we chose a densely populated satellite bin in the altitude of 550 km and inclination of 53 degrees as depicted in Fig. 8 (top), most of the satellites being the Starlink satellites (note that some of them are marked as debris). Here we found more than 1000 potential targets with an encounter rate of several satellites per day, when only several example relay mirror paths were calculated. For the conjunction calculation, we used Space-track.org and the theory/approach of the Simplified General Pertubations model SGP4. However, this approach is applicable to other altitudes as well.

The initial focusing distance of 10 km yielded only one conjunction per several days, so we gradually increased the focusing distance to 40 km. This raised the conjunction frequency to several events per day with each conjunction lasting from several tens of seconds up to a few minutes (Fig. 8 bottom).

Combining such a conjunction rate with a presumably much lower target revisit frequency, indicating when a particular target could be addressed a second time for further deceleration, it becomes evident that our proposal for relay-based debris remediation would not address a dedicated, single debris object, but rather aim to the stepwise deceleration and deorbit of an entire debris population at a given altitude and inclination. Preferably, this could be applied to the large multitude of small debris fragments which are much better accessible remotely with a laser beam than with dedicated ADR satellites picking them all up one by one.

If the relay satellite would be equipped with a laser-ablative drive using the post-mission disposal concept described above, the satellite could be then moved around the Earth using the ground laser to increase coverage and potentially interact with more debris that could be not only pushed from orbit, but also moved between different orbits and potentially gathered for recycle and re-use in space.

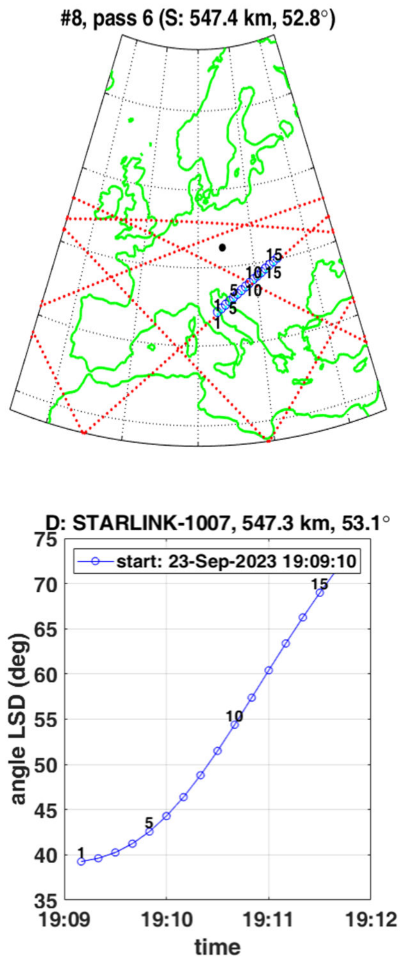

Figure 8. Sample conjunction of one debris simulation object with relay satellite and ground station: (top) Site location and relay satellite ground trajectory (bottom) Laser relay interaction angle (LSD angle, cf. Fig. 7).

5 SUMMARY AND OUTLOOK

At present, deorbiting defunct or aged-out satellites from LEO and partially from Medium Earth Orbit (MEO) is commonly studied to be performed actively via dedicated in-space transportation vehicles (ISTV). Those vehicles either grab the complete satellite and deorbit as package or attach a so-called de-orbit kit, which performs the deorbiting. However, orbital manoeuvres, in particular orbital changes require significant amounts of propellant.

Overcoming current propellant-related restrictions it becomes obvious from the findings of our study that deorbiting in PMD and ADR via a relayed laser beam as a ground-based energy resource paves the way for more versatile debris mitigation and remediation technologies capable to become disruptively more efficient when relieved from in-space power limitations.

In our conceptual study, the conjunction rate constitutes still a limiting factor, in particular for the triple conjunctions of ground station, relay satellite, and debris objects in relay-based ADR. However, following an in-orbit verification of these approaches, the implementation of a laser ground station network – and for debris additionally: a relay-satellite constellation – would greatly increase the concepts' efficiency for debris mitigation and remediation.

6 ACKNOWLEDGMENTS

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