USING THE USELESS: LASER PROPULSION UNIT FOR POST-MISSION DISPOSAL USING A LAUNCH ADAPTER AS PROPELLANT MATERIAL

Florian Scholl(1), Stefan Scharring(2), Raoul-Amadeus Lorbeer(2), Thomas Dekorsy(1,2), Wolfgang Riede(2), Lars Tiedemann(3), and Hanjo Schäfer(3)

(1) *Faculty of Aerospace Technology and Geodesy, University of Stuttgart, Germany, Email: f.t.scholl@web.de, thomas.dekorsy@itlr.uni-stuttgart.de*

(2) *German Aerospace Center (DLR), Institute of Technical Physics, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany, Email: {Stefan.Scharring, Raoul.Lorbeer}@dlr.de*

(3) *SpaceTech GmbH, Seelbachstraße 13, 88090 Immenstaad, Germany, Email: Lars.Tiedemann@spacetech-i.com*

ABSTRACT

We would like to address the growing task of space debris mitigation. For this purpose, we analyze the potential performance of laser-ablative propulsion using the launch adapter as propellant material. This might lead to a solution for end-of-life applications of spacecraft.
As a suitable sample laser system for space-based operation, we refer to an AEOLUS-like laser configuration, which would be capable of generating 0.9 mN of thrust at a specific impulse of 3000 s from aluminum as propellant. Simulations showing the possible capability of de-orbiting a 800 kg satellite from a 700 km orbit in 3.8 years under the use of 3.9 kg propellant. In addition, a first concept of the propulsion unit is drafted, including a foldable boom to guide the laser beam to the launch adapter.
Moreover, we give an outlook on in-orbit material processing options to improve the burn-up of structures, which are problematic for demise with the potential to reduce the risk of debris reaching the ground.

Keywords: laser-ablative propulsion; space debris mitigation; de-orbit methods; powered de-orbit; alternative propellants; impact-risk reduction; laser material processing, optimization of demise.

1. INTRODUCTION

1.1. Motivation

Laser-ablative propulsion (LAP), the process of using lasers to produce vapor or plasma from a target in order to propel the object in space via momentum transfer, has been studied for around half a century by now [1].
The concepts range from launch of payloads into orbit, trajectory modification of space debris from ground or space, to compact laser thrusters onboard the spacecraft itself [1]. So far, laser thruster units onboard of a satellite were mostly considered for attitude control tasks of nano- and micro-satellites as it was shown for example in the first successful in-orbit demonstration of such a propulsion unit by Ye et al. [2].
One of the big advantages of laser-ablative propulsion is the use of a huge variety of materials as propellant. Their usage was already investigated, ranging from dedicated polymeric or liquid fuels up to solid materials such as metals like gold or aluminum as it is shown in [1].
The latter gives the opportunity to use structural parts as propellant, which is especially interesting at the end-of-life of a satellite, where certain structures are not needed anymore to ensure the structural integrity of the spacecraft. A structural metallic component that is particularly suitable for this purpose is the launch adapter that remains on the satellite, which generally has no further function to fulfill after the launch. Further, the position of the launch adapter in relation to the center of gravity of the spacecraft is well known in order to ensure an exact prediction of the behavior of the spacecraft while releasing it from the rocket. This allows an improved estimation of the resulting thrust vector, depending on the location of the ablation spot on the target during operation.
Therefore, in this work we investigate the use of pulsed lasers mounted on the spacecraft itself to de-orbit satellites from a low Earth orbit (LEO) from altitudes where aerodynamic drag is insufficient for natural orbit decay, by assuming a launch adapter made from aluminum as fuel of the ablation process.

1.2. Scope of work

This paper is structured as follows:
In Sec. 2 the basic theoretical relations between the momentum coupling coefficient, specific impulse, thrust, and ablation efficiency, as well as the influence of the incident fluence are shown.
The determination of the performance data regarding the presented laser thruster unit is shown in Sec. 3 by defining the laser system based on the laser used in the instrument of the Aeolus mission, followed by considerations

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on impulse coupling and specific impulse, leading to the overall performance parameters.
A draft of the propulsion unit itself is presented in Sec. 4, including basic considerations on mass, volume, electrical power and thermal management.
The simulations of the de-orbit maneuver itself are shown in Sec. 5.2, while Sec. 6 gives a brief outlook on laser material processing options for demise preparation as an additional use of the LAP-unit.

2. THEORY OF LASER-ABLATIVE PROPULSION

The ablation process of metal targets is based on initial absorption of the laser radiation by the electron gas, followed by a relaxation and a transfer of the energy to the ion lattice according to the two-temperature model with a relaxation time in the picosecond range [3]. In this work we consider the use of short pulsed lasers with pulse durations τ_{p} greater than the relaxation times of metals. In this case vaporization of the material occurs during the laser pulse nearly simultaneously with respect to electron-ion coupling [3].

To describe momentum coupling by laser ablation the impulse coupling coefficient C_{m} can be defined according to [4] as the ratio between the laser-induced increment of target momentum $m\Delta v$ to the incident laser pulse energy E_{p}:

$$C_{\mathrm{m}} = \frac{m\Delta v}{E_{\mathrm{p}}} \tag{1}$$

Under the assumption of a monoenergetic exhaust stream ($m\Delta v = \Delta m v_{\mathrm{e}}$) the ablation efficiency $\eta_{\mathrm{AB}} \leq 1$, which links the momentum coupling coefficient to the specific impulse I_{sp} or respectively the exhaust velocity v_{e}, is defined according to [4] as follows, where g is the gravitational acceleration:

$$2\eta_{\mathrm{AB}} = \frac{\Delta m v_{\mathrm{e}}^2}{E_{\mathrm{p}}} = g C_{\mathrm{m}} I_{\mathrm{sp}} = C_{\mathrm{m}} v_{\mathrm{e}} \tag{2}$$

Using the definition of average optical power of a pulsed laser $\bar{P}_{\mathrm{opt}}$ as product of the pulse repetition frequency f_{rep} and the laser pulse energy

$$\bar{P}_{\mathrm{opt}} = f_{\mathrm{rep}} E_{\mathrm{p}} \tag{3}$$

allows to rewrite the impulse coupling coefficient to the continuous thrust T resulting from the ablation process as follows:

$$C_{\mathrm{m}} = \frac{\Delta m \cdot v_{\mathrm{e}}}{E_{\mathrm{p}}} = \frac{\Delta m \cdot f_{\mathrm{rep}} \cdot v_{\mathrm{e}}}{f_{\mathrm{rep}} \cdot E_{\mathrm{p}}} = \frac{\dot{m} \cdot v_{\mathrm{e}}}{\bar{P}_{\mathrm{opt}}} = \frac{T}{\bar{P}_{\mathrm{opt}}} \tag{4}$$

This allows to calculate the generated thrust directly from the optical power of the laser and shows at the same time the possibility of varying the thrust directly by changing the repetition rate and therefore the average optical power.

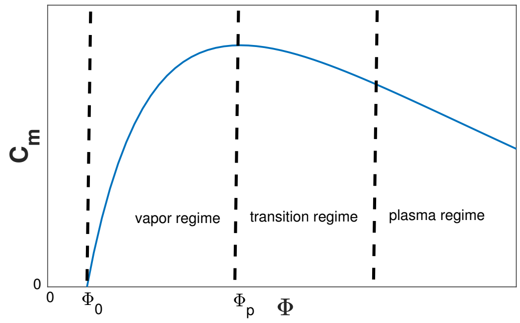

Figure 1. Principle sketch to visualize the influence of the fluence Φ on the momentum coupling coefficient C_m, described in [1], where C_m increases after the threshold fluence Φ_0 is surpassed with a maximum of C_m around the plasma threshold Φ_p. The decrease of the momentum coupling coefficient, after fluence is surpassing Φ_p, occurs due to plasma shielding.

The impulse coupling coefficient itself is strongly dependent on the material. In general, volume absorbers like polymers show a higher thrust caused by higher material removal and surface absorbers like metals with less material removal and therefore smaller thrust at a higher specific impulse [3]. Apart from being dependent on the material, the momentum coupling coefficient is influenced by the pulse duration τ_{p}, the wavelength λ and the incident fluence Φ and therefore often given as a function of $\Phi\lambda/\sqrt{\tau_{\mathrm{p}}}$ as a generalization for medium and high fluences [3]. To be more specific, the dependency of C_{m} on the incident fluence can be described as follows [3]:
While no momentum coupling occurs for small fluences below the ablation threshold Φ_0 and, hence, $C_{\mathrm{m}} = 0\ \frac{\mu\mathrm{N}}{\mathrm{W}}$ in that case, C_{m} rises strongly with increasing fluence once Φ_0 is surpassed. For short pulses, as considered in this work, the momentum coupling coefficient decreases after reaching the plasma threshold Φ_{p} at which plasma ignition occurs. By further increasing fluence, C_{m} is continuously decreasing due to plasma shielding of the target inside the plasma regime. Therefore, the maximum impulse coupling coefficient is reached around Φ_{p}. To visualize the dependency of the momentum coupling coefficient on the fluence, a principle sketch is shown in Fig. 1.

3. DETERMINING PERFORMANCE DATA

3.1. Laser system

As mentioned before, the concept provides for de-orbiting, which in general requires a higher thrust level than attitude control tasks, for which in-orbit laser

propulsion units were mostly considered in the past. In addition to that, the momentum coupling coefficient of aluminum is relatively small. For a large variety of laser configurations C_m amounts to 10 - 40 µN/W under optimum irradiation conditions [5]. Hence, we assume $C_m = 25\ \frac{\mu N}{W}$ in the following, noting that it is desirable to achieve an optical power which is as large as possible. Therefore, we used the performance data of the atmospheric laser doppler instrument (ALADIN) onboard the Aeolus-mission as a baseline for considerations how much optical power is realistically possible as an in-orbit laser unit. It has to be mentioned that the laser of ALADIN provided a spacial and spectral beam quality which is generally not necessary for the solely purpose of providing sufficient energy for the ablation process. As long as the desired fluence on target can be achieved, a lower beam quality is acceptable in order to obtain a less complex and therefore more economical system. However, it is considered an adequate baseline for estimating the maximum laser power that can be installed on a spacecraft.
The original ALADIN-laser, a frequency-tripled Nd:YAG laser, was operated at a wavelength of $\lambda = 354.89$ nm, a pulse duration of $\tau_p = 20$ ns, a repetition rate of $f_{rep} = 50.5$ Hz and a pulse energy of $E_p = 65$ mJ at the ultraviolet wavelength [6].
In comparison to the baseline of the ALADIN-laser, three changes were considered for the use in a potential LAP-system. At first it was assumed, that the laser is operated in the infrared range at $\lambda = 1064$ nm, which leads to an increased pulse energy for which $E_p = 360$ mJ was assumed, which equals the value of the ALADIN-laser after the final power amplifier [13]. To take into account further technological advances a repetition frequency of $f_{rep} = 100$ Hz was assumed.
Therefore, the average optical power calculates to $\bar{P}_{opt} = 36$ W according to Eq. 3.

3.2. Performance data

Regarding the overall performance of the propulsion unit the final values of thrust and specific impulse had to be calculated.
One of the big differences to chemical propulsion systems where the specific impulse I_{sp} is mainly dependent on the reaction itself, in laser-ablative propulsion it is only dependent on the intensity, while thrust can be adjusted independently according to the pulse repetition rate [1] and therefore the optical power of the laser.
For metal propellants being surface absorbers, a very high specific impulse can typically be obtained. Based on the simulation results presented in [7], an estimation of the specific impulse $I_{sp} = 3000$ s was assumed. Under the use of Eq. 2 and $C_m = 25\ \frac{\mu N}{W}$ this results in an ablation efficiency of $\eta_{AB} \approx 37$ %. A comparison with values for aluminum presented in [1] and [8], which are ranging from single-digit percentages to nearly 100 %, shows that this value is well conceivable.

Table 1. Summary of the performance data of the proposed laser propulsion unit

Parameter	Value
Wavelength λ	1064 nm
Repetition rate f_{rep}	100 Hz
Pulse energy E_p	360 mJ
Pulse duration τ_p	20 ns
Momentum coupling coefficient C_m	25 $\frac{\mu N}{W}$
Optical power $\bar{P}_{opt}$	36 W
Specific impulse I_{sp}	3000 s
Thrust T	0.9 mJ

By rearranging Eq. 4 the thrust calculates to:

$$T = C_m \cdot \bar{P}_{opt} = 0.9 \text{ mN} \quad (5)$$

The so determined thrust and specific impulse were used as input parameters for the simulations with the general mission analysis tool described in Sec. 5.2.
The overall performance and laser parameters are summarized in Tab. 1. To compare the performance values of the LAP-unit with those of conventional thrusters according to [9] and [10], an overview of thrust and specific impulse is shown in Fig. 2. In terms of specific impulse the value of the proposed LAP-system is higher than those of chemical propulsion systems, ranging up to a few hundred seconds, whereas in comparison to ion- and hall-effect-thrusters I_{sp} lies in the midfield. The thrust of the laser propulsion unit is at least one magnitude below the thrust values of all conventional systems. It has to be mentioned, that the thrust value shown in Fig. 2 for the LAP-system refers specifically to the thruster unit proposed in this paper. However, since the thrust is, apart from C_m, dependent on the average optical power, the gap to the conventional systems could be closed in theory by increasing the optical power.

4. DRAFT OF PROPULSION UNIT

4.1. Description of the propulsion unit

In general, a possible laser propulsion unit could consist of two main subsystems, the laser itself and a beam delivery system to focus the laser beam onto the surface of the target, in this case the launch adapter.
Our concept provides for a beam delivery system consisting of a foldable boom, including free-beam optics to deliver the beam from the laser inside the spacecraft to a scanning unit at the end of the boom, in order to focus the laser beam onto the launch adapter cf. the technological concept lined out in [11]. Fig. 3 shows a schematic illustration of the beam delivery system mounted on a satellite. In this case the boom consists

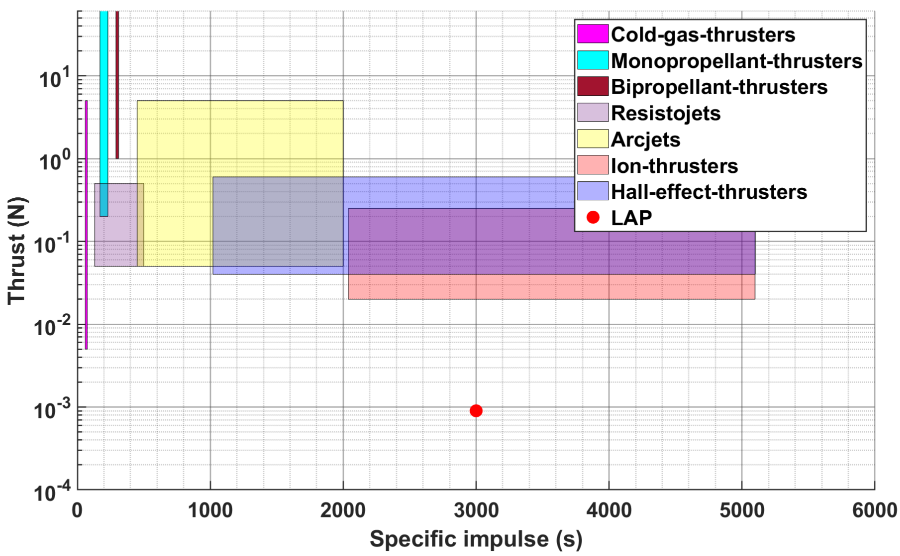

Figure 2. The performance parameters thrust and specific impulse shown in comparison to typical ranges of chemical propulsion systems (cold-gas-thrusters, monopropellant-thrusters, bipropellant-thrusters) according to [9] and electric thrusters (resistojets, arcjets, ion-thrusters, hall-effect-thrusters) according to [10]. From the technologies mentioned above, at the moment only monopropellant-, bipropellant-, ion-, and hall-effect-thrusters are seen as suitable for the purpose of de-orbiting.

of three foldable struts. During the launch the folded struts including the scanning unit can be securely stored inside a cavity in the center of the launch adapter. To operate the laser propulsion unit, the struts are unfolded and locked in place. The scanning unit at the end of the boom divides the laser beam into two parts and focuses them at opposite positions of the rim of the adapter, to ensure a centered thrust vector if the beam is divided into two equal parts. By introducing an asymmetry of the irradiation times and changing the location of the focal spots around the rim of the launch adapter, the attitude of the spacecraft can be controlled over two axes. The laser beam is focused on the adapter at under an oblique incidence angle to reduce interactions of the beam with the ablated material.

Although the incident angle of the beam allows a certain distance of the scanning unit to the target, protection of the optics is a major challenge. Especially in the cold vacuum environment of space, their surfaces can easily get contaminated by deposition of the ablated material. Even though there are concepts which use a dedicated ablation propellant on a target tape which is ablated by transmitting incidence of the laser beam, so-called transmission mode protecting the optics [4], unfortunately this principle is not applicable to our concept. Instead, a protective window could in principle be used between propellant and laser optics which, during certain maintenance intervals is cleaned using as well laser ablation, however, with a defocused beam at low fluences, cf. [12].

Solving this problem is regarded as critical and has to be subject of future research.

4.2. Considerations on further system parameters

Because the exact design of the beam delivery system is strongly dependent on the shape of the actual spacecraft, exact calculations on mass and volume of the boom are difficult to perform at the current status of our investigations. Hence we focus mainly on the laser system itself.

For considerations on mass and volume the ALADIN-laser gives a first orientation. The system consisted of three main parts: the reference laser head (RLH) with a volume of 2 liters and a mass of 2 kg, the power laser head (PLH) with a volume of 30 liters and a mass of 30 kg, and the transmitter laser electronics (TLE) with a volume of 25 liters and a mass of 22 kg [13]. Therefore, the whole system equaled to 57 liters of volume and 54 kg of mass. Taking into account the advances in laser technology since the development of the ALADIN-laser until the operational readiness of a potential laser thruster unit, these values should decrease drastically. In addition to that a laser solely for the purpose of ablative propulsion could be built less complex, due to simpler beam conditioning and elimination of components for harmonic generation compared to the laser which was used in the instrument. This should lead to a further decrease in volume and mass.

Regarding the electrical power consumption and required cooling capacity a wall-plug efficiency of $\eta_{\rm wp} = 25\%$ [14] for typical diode-pumped solid-state lasers was assumed. This results in a electrical power consumption of:

$$P_{\rm el} = \frac{\bar{P}_{\rm opt}}{\eta_{\rm wp}} = 144 \text{ W} \tag{6}$$

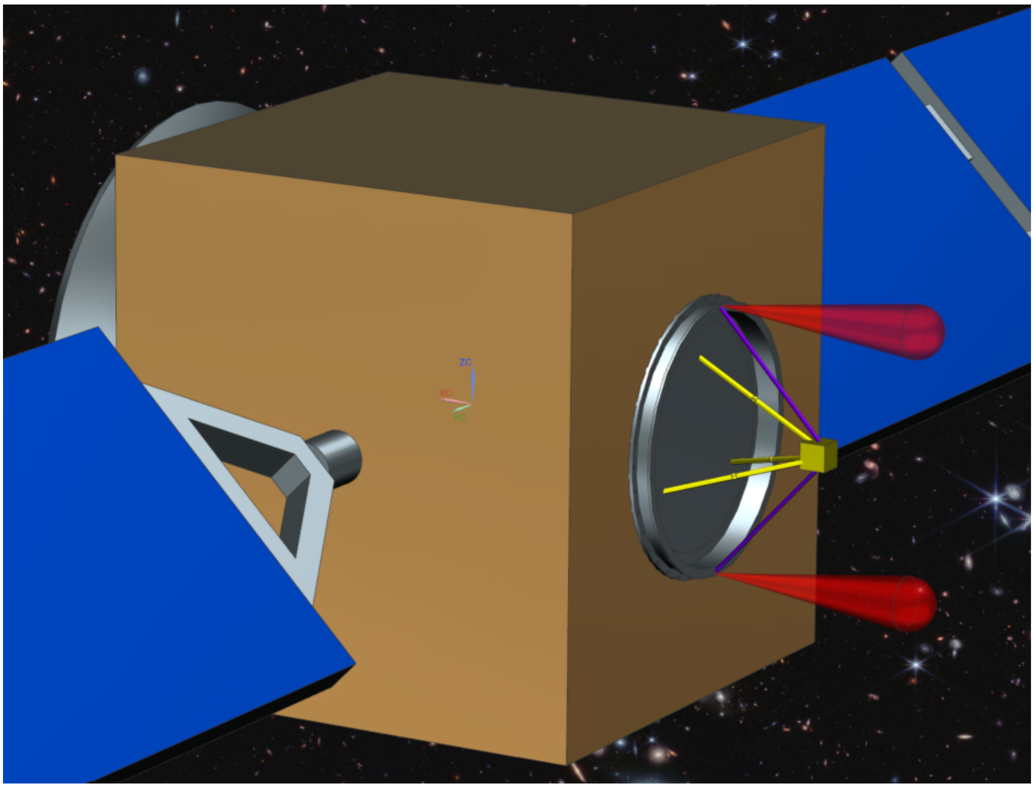

Figure 3. Spacecraft with LAP-unit. Visible is the deployed boom, shown in yellow, consisting of three struts, mounted in the center of the launch adapter with the scanning unit at the end. The plumes formed from ablated material are shown in red. The symbolized laser beams are shown in purple and for the sake of visibility hugely over-sized.

Since the needed cooling capacity results directly from the difference of the electrical power and the optical power it calculates to:

$$\dot{Q}_{\text{cooling}} = P_{\text{el}} - \bar{P}_{\text{opt}} = 108 \text{ W} \tag{7}$$

The original ALADIN-laser was cooled by a cold plate connected to a radiator via heat pipes [13]. The cooling capacity is seen as an important factor, limiting the increase in optical and therefore electrical power without adding a lot of drag area, mass, and system complexity by increasing radiator area or even resulting in the need of actively pumped cooling circuits. It was shown by Wernham et al. [15], that for the laser used in the Aeolus mission 4 W of optical power at the ultraviolet wavelength was produced from 300 W of electrical power. Therefore, the cooling capacity from Eq. 7 should be well conceivable due to the lack of additional components, such as harmonic generation including the beam dump [13] for the proposed laser system.
A closer look on Eq. 6 and Eq. 7 shows that a change of the laser type to ones with greater wall-plug efficiency would allow to increase the thrust from an enhanced electrical and therefore optical power, while leaving the cooling capacity untouched. Thus, a future development of space qualified lasers with higher wall-plug efficiencies and matching optical power levels are seen an important step towards closing the gap to conventional propulsion systems, already shown in Fig. 2.

5. DE-ORBIT MANEUVER

5.1. Orbit and satellite parameters

The altitude of the initial orbit was chosen in a way that aerodynamic drag is insufficient to de-orbit a satellite within 25 years described in [16]. At an altitude of 600 km to 700 km the orbit lifetime lies generally between 15 and 78 years, depending on the ballistic coefficient of the spacecraft and the solar activity [17]. Therefore, an initial circular orbit with an altitude of 900 km was chosen, which is well above the mentioned altitude range.
Regarding the spacecraft itself a satellite with a mass of $m_{\text{sat}} = 800$ kg and a projected surface area of $A_{\text{ref}} = 10 \text{ m}^2$ was assumed.
To account for atmospheric drag, a drag coefficient of $c_{\text{d}} = 2.2$ for typical satellites was used as preset value in the simulation tool described under Sec. 5.2. Hereby the ballistic coefficient of the satellite calculates to [17]:

$$\beta = \frac{c_{\text{d}} \cdot A_{\text{ref}}}{m_{\text{sat}}} = 2.75 \cdot 10^{-2} \frac{\text{m}^2}{\text{kg}} \tag{8}$$

5.2. Simulations

For simulating the de-orbit maneuver the general mission analysis tool (GMAT) was used, which is a space mission design software for the design and optimization of missions ranging from LEO- to deep space missions [18]. GMAT was used in the version R2022a.
The gravity field of the Earth was represented by the joint gravitational model JGM-2 up to fourth degree and order. To account for aerodynamic drag the MSISE-90 atmospheric model was used. As input parameter for the atmospheric model the $F_{10.7}$-index $F_{10.7} = 122$ sfu was used as arithmetic average over the values from 1957 until 2024 gained from the space weather file from [19]. To calculate the trajectory a Runge-Kutta-based orbit propagator was used.
The laser ablative propulsion unit was represented as electric propulsion system under the use of constant thrust $T = 0.9$ mN and specific impulse $I_{\text{sp}} = 3000$ s. This assumption justifies due to the low thrust level of the LAP-system, which requires a maximization of thrust duration per orbit revolution to reduce the overall maneuver time. This results in a typical low-thrust trajectory by spiraling towards the re-entry altitude. To verify that the assumed initial orbit altitude leads to a duration of natural decay which is greater than 25 years, a simulation without active propulsion system was performed, followed by the propelled de-orbit maneuver. Both simulations were performed to a final re-entry altitude of 100 km.

5.3. Results

The simulation of the natural decay from the circular orbit with an initial altitude of 900 km shows a de-orbit duration of $\tau_{\text{nat, 900 km}} = 86.7$ years. This value clearly exceeds the requirement for active de-orbiting of 25 years from [16]. Therefore, the chosen altitude is well suited for a powered de-orbit maneuver.
The according simulation of the active de-orbit from 900 km results in a duration of $\tau_{\text{LAP, 900 km}} = 6.76$ years under the use of a ablated propellant mass of $m_{\text{f, LAP, 900 km}} = 6.5$ kg.
The achievable velocity change Δv can be calculated using the Tsiolkovsky rocket equation [9]:

$$\Delta v = g \cdot I_{\text{sp}} \cdot ln\left(\frac{m_{\text{sat}}}{m_{\text{sat}} - m_{\text{f}}}\right) \quad (9)$$

The calculation of the velocity change according to Eq. 9 results in $\Delta v_{\text{LAP, 900 km}} = 240 \ \frac{\text{m}}{\text{s}}$.

The ALADIN-laser, used as baseline for the propulsion unit was designed for a lifetime of 3 years. Since this value is far below the duration simulated for the active de-orbit maneuver, it is considered not feasible with the defined LAP-system. Therefore, the initial orbit altitude was decreased to 700 km for subsequent simulation runs. The duration for the natural orbit decay from 700 km altitude resulted in $\tau_{\text{nat, 700 km}} = 29$ years which is still over the requirement of 25 years for active de-orbiting. The required duration and propellant mass reduced to $\tau_{\text{LAP, 700 km}} = 3.8$ years and $m_{\text{f, LAP, 700 km}} = 3.94$ kg respectively. Since the results regarding the de-orbit duration is in the vicinity of the designed lifetime of the ALADIN-laser the active de-orbit maneuver from an altitude of 700 km is considered feasible in theory. An overview ofthe simulation results is given in Tab. 2.

Table 2. Overview of the simulation results regarding duration and required ablated propellant mass for natural orbit decay and active de-orbiting via LAP-system from a circular orbit with an initial altitude of 700 km and 900 km.

Simulation	Duration (a)	prop. mass (kg)
Natural decay 900 km	86.7	-
Active de-orbit 900 km	6.76	6.5
Natural decay 700 km	29.0	-
Active de-orbit 700 km	3.8	3.94

Fig. 4 shows the curves of altitude over time for the natural decay and the active de-orbit maneuver via LAP-unit from circular initial orbit of 700 km altitude. The slight oscillations of the altitude result from an oscillation of eccentricity combined with the underlying geoid. Since their magnitude stays constant over the simulation the oscillations are regarded as negligible as the main goal is to visualize the development of the average altitude over the maneuver, which is clearly visible.
Fig. 4 clearly highlights the accelerated de-orbit compared to the natural decay. However, due to the low thrust level, the de-orbit can be regarded as accelerated, but not as controlled, since the comparably long duration in relation to conventional chemical propulsion systems usually used for this purpose does not allow an exact estimation of the final reentry location.

6. MODIFICATION FOR DEMISE

De-orbiting by the laser propulsion unit can be regarded as an accelerated re-entry, but not as a controlled entry in the classical sense, as the final entry location is difficult to estimate due to the low thrust level. For satellites with very robust monolithic structures, such as mirrors, especially from ceramic materials, that are difficult in terms of demise during re-entry, a controlled entry using engines with high thrust is often necessary.
Therefore, in-orbit material processing for demise preparation could be an additional use-case for the laser system in the further future. By designing the boom in a way that the laser beam can be focused on these structures the laser could be used to drill holes into the structures to increase the surface interacting with the re-entry plasma, which improves the behavior in terms of demise by accel-

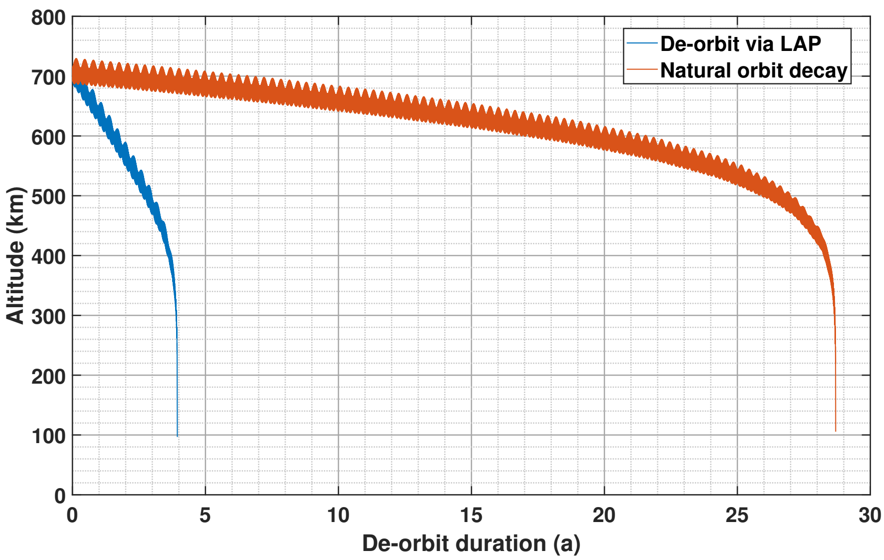

Figure 4. Comparison of the altitude over time curves of the de-orbiting of an 800 kg satellite from a 700 km orbit as a result of the simulations in GMAT. It shows clearly the decreased de-orbit time of 3.8 years for the active de-orbit via LAP in relation to 28 years for the natural orbit decay.

erating this process. Therefore, in analogy to the design for demise, we call this method modification for demise (patent pending).

Especially exposed mirrors of telescope optics facing away from the spacecraft seem to be an interesting application. Not only are they easily reachable by the laser beam delivered by the boom, but due to their orientation an additional propulsion effect as described for the launch adapter could be achieved simultaneously. To calculate possible performance parameters for the synergistic use of material processing and propulsion at the same time further research on momentum coupling of these materials would be helpful.

However, due tho the improved behavior in terms of demise, the required precision of re-entry could be reduced and at best making a controlled re-entry obsolete, mitigating the risk of hazard on ground.

7. CONCLUSIONS AND OUTLOOK

It was shown, that a laser propulsion unit with 20 ns pulse duration, 1064 nm wavelength and 360 mJ pulse energy with a pulse repetition rate of 100 Hz, similar to the ALADIN-laser from the Aeolus mission should be capable to de-orbit a satellite with a mass of 800 kg much faster from a circular orbit of 700 km altitude, by using a launch adapter made from aluminum as propellant. While applying a thrust of 0.9 mN combined with a specific impulse of 3000 s around 4 kg of material would be used over a period of 3.8 years for this purpose.

Furthermore, an outlook on possible material processing options in the future was given. The method of modification for demise would allow to perforate big monolithic structures, which are usually problematic in terms of demise while re-entry, to increase the surface interacting with the re-entry plasma improving the burn up. By this method the risk of hazards on ground due to debris residue could be reduced.

Although we showed that in theory the presented concept of a laser propulsion unit is capable of de-orbiting a LEO-satellite from altitudes where atmospheric drag is insufficient for natural decay in 25 years, there are still a lot of challenges to face in order to substantiate the concept towards realization. At first an improved understanding of the resulting performance parameters, in particular the specific impulse, is necessary to enhance the precision of predictability. The main goal in terms of performance is seen in the enhancement of thrust to close the gap to conventional propulsion systems and shorten the de-orbit time. Therefore, laser systems with higher wall-plug efficiencies are seen as crucial.

An additional possibility to increase the usable power would be to separate the laser source from the target by using a laser satellite to perform a non-contact de-orbit of the object, similar to the approach presented by Schall [20]. The laser as the main payload of the satellite would allow higher limits regarding the parameters discussed in Sec. 4.2.

In terms of technological challenges regarding the beam delivery system the protection of the optics from ablated material is seen as critical and has to be subject of future research as well. In addition to that, a decrease in mass and volume of the laser-system itself is seen as a main goal on the way towards a possible realization of the concept.

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