A Systematic Study of Laser Ablation for Space Debris Mitigation

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Abstract
Laser ablation refers to the ejection of matter from the surface of a material heated to high temperature by a laser beam. The thrust produced in the direction opposite to the ejected mass can be used to alter the orbit of an object in space. The Trento Institute for Fundamental Physics and Applications (TIFPA) participates in *New Reflections*, a 3 y interdisciplinary experiment of the Italian Institute of Nuclear Physics (INFN). The experiment is devoted to the development of laser technologies for space in the fields of geo-referencing, tracking, propulsion and debris mitigation. The initial results of the TIFPA activity concerning debris mitigation are presented.

Keywords : laser ablation, space debris mitigation, simulation analysis

Introduction
The members of the TIFPA group in *New Reflections* include material scientists of the IdEA Laboratory of the University of Trento, specialized in the field of laser ablation (A. Peterlongo), which is studied at the IdEA pulsed laser deposition facility (M. Bonelli), and physicists with a long experience in the development of instruments for fundamental research (W.J. Burger) and practical applications in space (F. Ambroglini).

The performance of ground and space lasers for debris mitigation is evaluated with a simulation program. Results for two cases, 10 and 500 kg masses in an polar orbit, an orbit representative of the major part of the debris population in Low Earth Orbit (LEO), are presented with the corresponding laser configurations compatible with the simulation results. A key parameter for the laser specification is the coupling coefficient relating the thrust generated by the ablated material to the incident laser power, C_m (N/W). The coupling coefficient of aluminium, a common material in satellite construction, has been measured by the IdEA Laboratory.

Orbital Mechanics
The Hohmann transfer shown in Fig.1 is the kinematically optimal manner to change the orbital altitude of a satellite. Two thrusts are applied in the direction opposite (parallel) to the orbital velocity to lower (raise) the altitude.

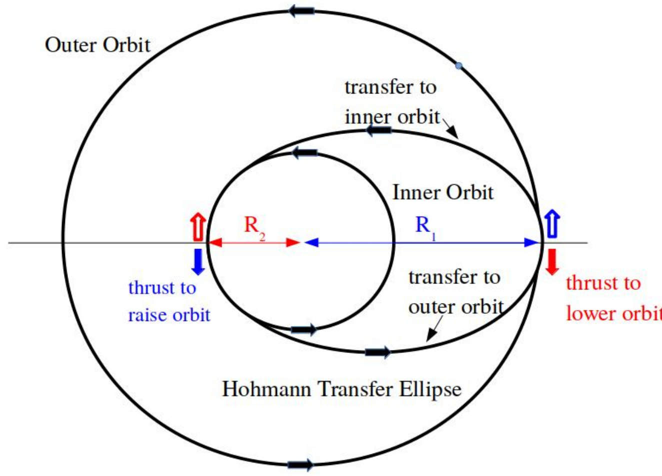

Figure 1 : The Hohmann transfer used to change the satellite altitude

In the case of debris mitigation, the thrust delivered by a ground laser will always have a component directed away from the Earth. A space laser may engage debris targets at lower and higher altitudes. The orbital changes of a 500 kg debris mass initially in a circular orbit at an altitude of 600 km, by a thrust in the direction opposite to the orbit velocity (Hohmann), and thrusts in the radial directions toward the local zenith direction, and toward the Earth, are shown in Fig. 2. In each case, the result is an elliptical orbit with a perigee which approaches the Earth. The debris is effectively eliminated by the orbital decay due to the frictional drag encountered once it enters the upper atmosphere (~200 km).

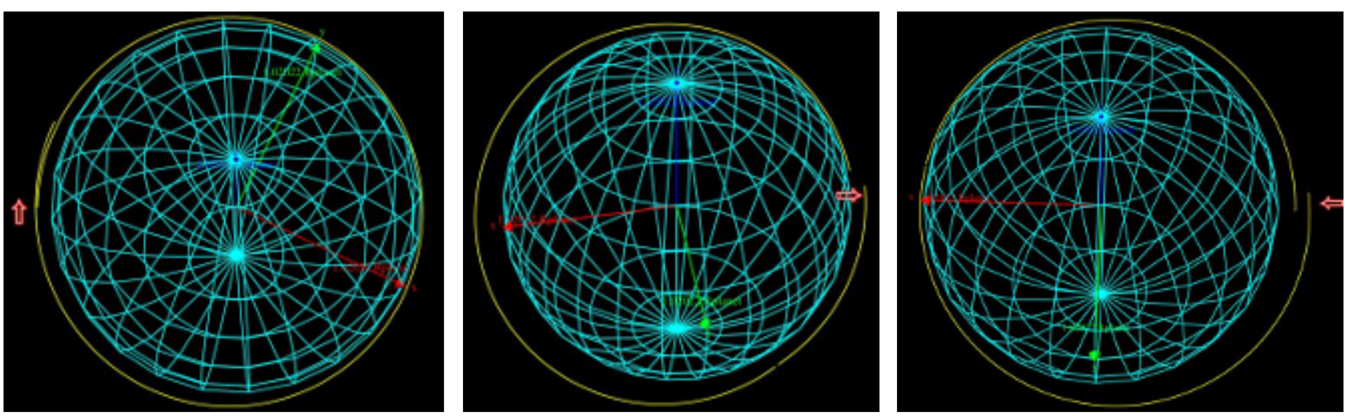

Figure 2 : The modification of the circular orbit of a 500 kg mass by thrusts in the direction opposite to the orbital velocity (left), in the radial direction towards the zenith (center) and in the radial direction towards the Earth (right). The thrust is applied 16.7 min. after the simulation begins. The period of the initial circular orbit is 97 min.

Debris Simulation

A simulation developed in Matlab© is used to evaluate the performance of space and ground lasers. Four laser deployment scenarios are considered : a dedicated satellite in polar orbit (SAT), a laser installed on the International Space Station (ISS), and two ground lasers located in the equatorial (GEQ) and northern polar (NPO) regions.

The laser beam delivers a 1 N thrust each second acting along the line-of-sight (LOS) between the laser and debris positions. The laser is switched on when the debris approaches the ISS or SAT, and the LOS is not obscured by the Earth, defined as a spherical volume with a radius[1] $R = R_E + 200\ km$. The ground lasers are switched on during the approach of the debris with an angle of elevation of the LOS relative to the zenith less than 55°, corresponding to an atmospheric transmission efficiency of 70-82% (E. Wnuk). The laser is switched off at the moment the distance between the debris mass and laser position increases.

The Jacchia-Bowmann 2008 model (B.R. Bowmann) is used for the air density at high altitudes. The model takes into account the density fluctuations due to diurnal and seasonal thermal variations. The epoch January 1, 2010, h.00:00:00.0 is chosen as the starting point in the simulation in order to use known solar values for the calculation of the atmospheric density. The debris is represented as a point mass in the simulation. The surface-area-to-mass ratio (A/M) and drag coefficient (C_D) are chosen to yield a constant ballistic coefficient, $\beta^* = C_D \cdot \frac{A}{M} = 0.1,$ to compute the frictional drag.

The orbital elements of the debris mass, ISS and SAT at epoch are listed in Table 1. The debris mass starting position is the apogee of the orbit (800 km). The starting point of the SAT is the perigee (500 km). The SAT altitude and inclination angle are chosen with respect to the debris mass orbit to optimize the performance.

Table 1 : The orbital parameters of the debris mass, ISS and SAT : semi-major axis a, eccentricity e, inclination i, right ascension of the ascending node Ω, the argument of the perigee ω, and the true anomaly θ.

	A	E	I	Ω	ω	θ
debris mass	7170 km	0.001	100°	0°	180°	180°
ISS	6780 km	0.0016	52°	128°	99°	313°
SAT	6885 km	0.001	80°	180°	90°	0°

The position of the GEQ laser at epoch is on the x-axis of the Earth Centered Inertial (ECI) reference system drawn between the centers of the Earth and the Sun, at a distance of the 6378 km from the Earth's center. The GPO laser, latitude 80° N, is at a distance of 6357 km from the Earth's center, placed to have the debris mass at its zenith at epoch. The orbital direction of the debris mass (i > 90°) is opposite to the rotation of the Earth, and to the orbital directions of the ISS and SAT.

Simulation Results

The simulation results for the 10 and 500 kg debris masses are presented in Fig. 3. The optimized orbit chosen for the SAT, with respect to the debris orbit, results in an immediate effect on the 10 kg mass, whereas ~12 h are required before the debris mass encounters the laser at the lower inclination angle orbit on the ISS (upper-left graph in Fig. 3). The observed step structure characterizing the perigee evolution reflects the frequency of the laser-debris encounters. The lower altitude limit of 100 km was used for the NPO simulation. The gray sections of the NPO curves indicate the perigee altitudes where a decrease of the orbital velocity is observed due to the frictional drag in the atmosphere. In all other cases, the observed decrease in the perigee altitude corresponds to an increase of the orbital velocity due to the gravitational acceleration resulting from the modification of the debris orbit by the ground and space lasers.

[1] $R_E = 6378\ km$

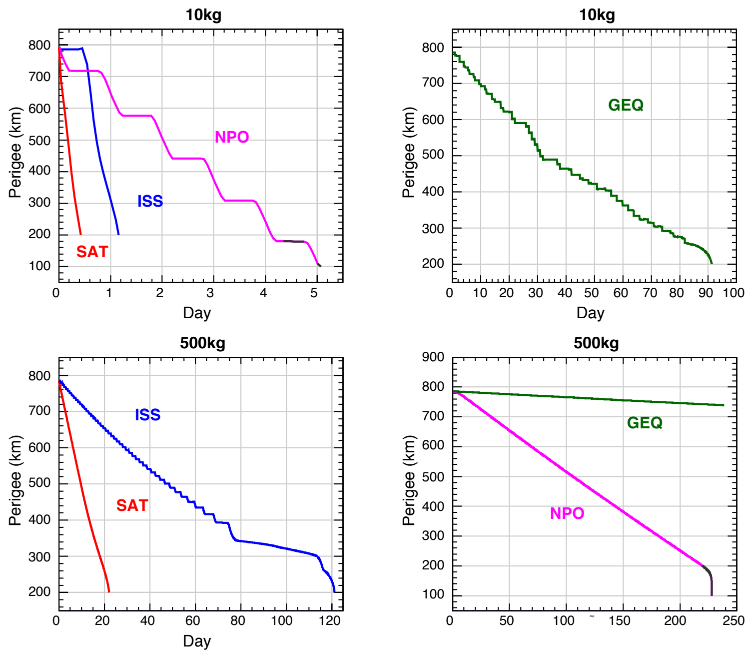

Figure 3 : The simulation results for the space (ISS/SAT) and ground (GEQ/NPO) lasers for the 10 and 500 kg debris masses. The gray segments (NPO) indicate perigee changes due to the frictional drag in the atmosphere.

The simulation results are summarized in Table 2. The lasers of the ISS and GEQ (10 kg mass) require a 50% larger total impulse than their polar counterparts to achieve the same result. The GEQ laser reduces the perigee altitude of the 500 kg debris mass by 54 km after 240 d. The difference in performance is particularly important for the ground lasers.

Table 2 : The total simulation time t_{tot} , total time laser on t_{laser} , the fraction of time the laser is on, the total impulse delivered to the debris mass and the final altitude after time t_{tot}

	10 kg debris mass					500 kg debris mass				
	t_{tot}	t_{laser}	t_{laser}/t_{tot}	Impulse	Alt. Final	t_{tot}	t_{laser}	t_{laser}/t_{tot}	Impulse	Alt. Final
	d	h	%	Ns	km	d	h	%	Ns	km
ISS	1.16	1.32	4.7	$4.8 \cdot 10^3$	200	121.3	62.2	2.14	$2.2 \cdot 10^5$	200
SAT	0.43	0.83	8.0	$3.0 \cdot 10^3$	200	22.1	41.5	7.8	$1.5 \cdot 10^5$	200
GEQ	91.3	1.79	0.08	$6.4 \cdot 10^3$	200	240	9.2	0.16	$3.3 \cdot 10^4$	746
NPO	5.07	1.15	0.95	$4.3 \cdot 10^3$	100	228	48.0	0.88	$1.7 \cdot 10^5$	100

Laser Parameters Compatible with the Simulation Results

The simulation results are obtained with a thrust of 1 N delivered each second. The corresponding laser pulse energy E_o may be estimated with the expression (E. Wnuk)

$$m\Delta v = E_o T_{atm} T_{tel} \left(\frac{A}{\pi\varphi^2(r)}\right) C_m \qquad (1)$$

with $m\Delta v = 1$ Ns, the debris mass m, the atmospheric and telescope transmission efficiencies T_{atm} and T_{tel} , the coupling coefficient C_m for the conversion of the incident laser pulse power to thrust (N/W), the debris surface area A, and $\pi\varphi^2(r)$ the laser spot size at the distance r.

The aluminium coupling coefficient measured by the IdEA laboratory with a 20 ns pulse width is compared to values reported for smaller and larger pulse widths in Fig. 4. The open circle refers to the coupling coefficent value cited in (T. Ebisuzaki) for pulse widths below 1 ns (C. Phipps). In the pulse width range between 1 and 30 ns, C_m varies by a factor of five.

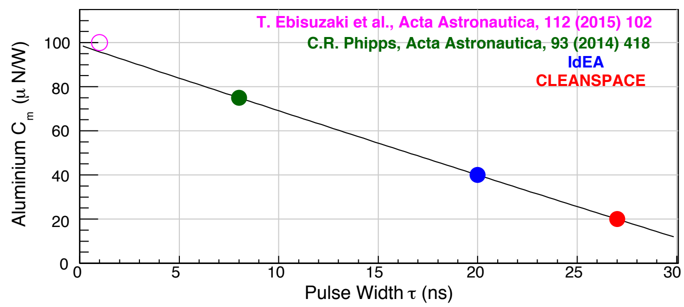

Figure 4 : The values of the aluminium coupling coefficients reported with different pulse widths. The data (filled circles) are described by a line fit.

The pulse energies E_o, peak power and power densities are shown in Fig. 5 for space and ground laser configurations compatible with the simulation results for the 10 kg debris mass.

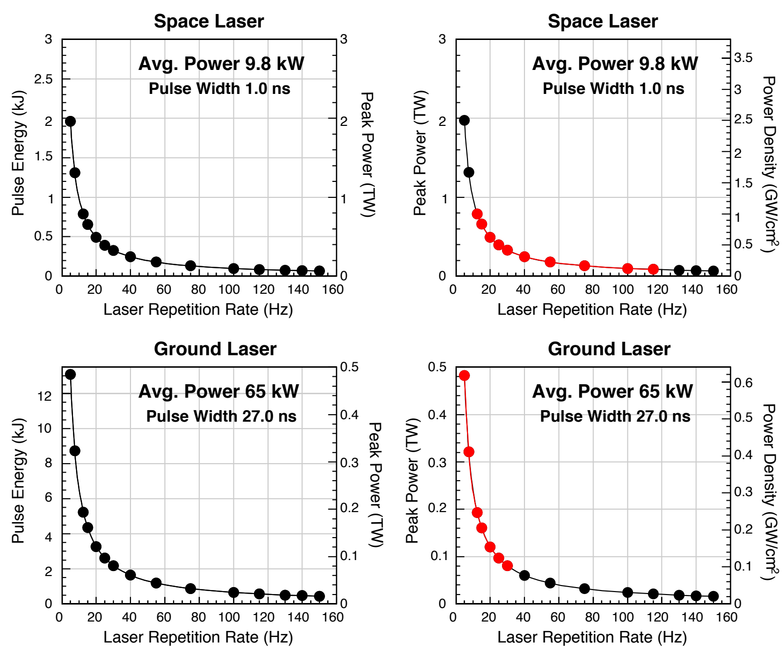

Figure 5 : Pulse energy, peak power and power density for space and ground pulsed laser configurations compatible with the simulation results for the 10 kg debris mass. The operational ranges in repetition rate corresponding to the power density required for ablation are indicated in red.

The pulse energy E_o is computed with $T_{tel} = 0.8$, $T_{atm} = 0.75$ for the ground lasers (1.0 for the space lasers), and $A = \pi\phi^2(r) = 1\mathrm{m}^2$. The pulse widths of 1 and 27 ns are chosen respectively for the space and ground lasers, the corresponding coupling coefficients, 100 and 27 μN/W, are used in Eq. 1.

The IdEA and CLEANSPACE coupling coefficients reported in Fig. 4 refer to the peak values of C_m in the power density range between 0.5 and 1.5 GW/cm^2. The measured vaporization thresholds are ~0.1 GW/cm^2. The power density energy range between threshold and 1.5 GW/cm^2 is indicated in Fig. 5 to show the effective operational frequency range of the two pulsed lasers.The coupling coefficient and energy density threshold are the key parameters affecting the performance and power requirements of the laser, the latter critical for a space laser, where small pulse widths, high frequencies impose.

Conclusion

The diversity of the debris population in terms of the size and mass of the objects and their orbital distribution, is a fundamental consideration for the evaluation of technology solutions proposed to reduce the population. Consequently, the first objective was the development of the orbital simulation in order to define the required laser configurations with respect to these parameters. The results presented for the polar orbit debris masses indicate clearly the avantage of a space laser in polar orbit, or a ground laser located at high latitude. The performance estimates are somewhat optimistic. For example, the variation of the laser spot size at the target $\varphi^2(r)$ should be implemented in the simulation. The ultimate goal is to quantify the different effects and provide a systematic survey of the applicability of the technology for the different debris populations.

The Laboratory IdEA has an essential role, illustrated by the information presented in Fig. 4 concerning the aluminium coupling constant behavior with pulse width. In addition to the experimental measurements, the laboratory possesses a competence in numerical calculations which model the underlying physics. An understanding of the underlying physics is fundamental to technological innovation. The possible innovations are likely to be more numerous for the propulsion application.

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