Positioning of space objects by laser-induced jets

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Abstract. Laser-induced thrust provides a number of significant advantages over the currently used methods: virtually any material can be used as a working medium; radiation source and its power unit can be located outside the spacecraft; it is possible to provide a minimum impulse bit of 1 nN s or less; momentum imparted at single impact can be controlled within 2 orders of magnitude dynamic range. We have considered recoil momentum generation at femtosecond to continuous laser impact range on different materials normalized by laser output performance to evaluate momentum coupling to on-board energy system. It is shown that better momentum coupling at short wavelength is not worth of associated energy losses, but laser pulse shortening to picosecond range is. Data reported here on laser thrust generation efficiency and methods of laser impact layout are of interest not for small spacecraft application range broadening only, but also for the prevention of emergency situations development (launch to unplanned orbit, uncontrolled rotation, etc.), space debris removal, and anti-asteroid protection of the Earth – possible impact layouts for such missions are considered.

1. Introduction
Accumulation of space debris on Earth orbits is a global challenge. Uncontrolled growth in debris number, with yearly increasing probability, can lead to mass destruction of satellites and cancellation of space launches (Kessler syndrome). The greatest probability of damage caused by space debris is observed on polar orbits (1000 km/82°, 800 km/98°, 850 km/71°). Unlike many other countries, orbits with such inclination are required to fully cover the territory of Russia. Not only Russia as one of the leading space-faring nations, but also the entire global community, is interested in response to this challenge. Number and status of organizations monitoring the situation on Earth orbits is growing as awareness of space debris danger does (UN Inter-Agency Space Debris Coordination Committee, NASA Orbital Debris Program Office, etc.). Currently, a number of programs for active space debris removal using specialized spacecraft are being prepared for implementation: DEOS, CleanSpace, ADR1EN, BETS, RemoveDEBRIS [1, 2]. The relevance and importance of the development of economically attractive method of Earth orbits cleaning from space debris can not be overestimated.

After mission accomplishment, according to ISO 24113:2011 standard, spacecraft is to be removed from the orbit in 25 years. E.g., for CubeSat 1U estimated removal time from 520 km orbit is 28 years. A number of methods had been suggested for space debris removal, those can be divided into the following groups: electrodynamic drag; impact deceleration; aerodynamic drag; collecting and towing spacecraft with nets or other engagements; external jet impact; impact of powerful ground- and space-
based lasers [3]. All these approaches have their advantages, disadvantages and scope, but still none used in practice [1, 4]. High cost of a single object removal is the main problem of proposed solutions implementation [5] (for objects of ca. 1 ton, it is comparable with the same mass launch to low-Earth orbit (LEO) [6]).

It is well known that the cost of 1 kg payload launch to LEO is comparable to the cost of the same mass of gold. So it would be reasonable to use space debris (total mass estimate is 8 thousand of tons: 97% are 4863 satellites and 18 835 rocket stages and their fragments [7]) as a working medium for spacecraft thrusters. The only possibility for this at the moment is evaporation (and subsequent ionization) using laser radiation (charged particles beams are also possible though). Implementation of this approach would change the economy of interplanetary flights and inter-orbital towing radically; it was suggested for the first time in [8]. However, it is clear that it is not suitable for any space debris object. Therefore, in addition to the development of physical and technical bases, it is necessary to develop recommendations on the scope of this and other methods.

In addition to space debris removal, presented results could be also used for anti-asteroid protection of the Earth; position control of small spacecraft not equipped with propulsion systems (including nano- and picosatellites, which would significantly expand their scope of application); to create systems using elements of rigid structures, the need for which disappears after the spacecraft launch to LEO, as a working medium for laser propulsion system; for the use of meteoroids and other celestial bodies or their fragments as a working medium for interplanetary flights. Data on the impact regime influence on droplets formation could be used for planning of missions for asteroids and other celestial bodies material samples collection for composition analysis without landing.

2. Performance of laser thrust

Maximum value of thrust normalized to the laser radiation power (momentum coupling coefficient) for metals lays within $10^{-5} \div 10^{-4}$ N/W (up to $5 \times 10^{-4}$ N/W at ultrashort irradiation), is strongly dependent on laser fluence, and maximum values are achieved near the plasma formation threshold [9, 10] (~4.5 times higher than laser ablation threshold of 0.1÷1 J/cm$^2$ order at nanosecond impact [11]). For many materials, it is shown that laser ablation energy threshold decreases proportionally to the square root of pulse duration down to ca. 100 ps [12, 13], while at further pulse shortening threshold almost does not change. Thus, lasers with pulse duration of about 100 ps should be used to minimize the average laser radiation power.

Traditionally, momentum coupling coefficient is considered versus laser intensity $I_0$ or CNK-parameter $I_0 \tau^{1/2}$ [14]. At long distance laser radiation transfer, shorter wavelengths should be used to reduce the divergence effects. However, with pulse duration and wavelength decrease, the electro-optical efficiency of laser systems tends to decrease also, so it is important to have data on laser thrust generation efficiency in the widest possible range of pulse durations and wavelengths and the maximum variety of materials that make up space debris, for the subsequent optimization of the mass-dimensional, energy-power and spectral characteristics of laser systems.

### Table 1. Reference efficiencies of lasers at fundamental frequency.

| CO$_2$-laser | Eximer | Laser diode (e-o) | Nd DPSS (o-o) ns | Ti:Al$_2$O$_3$ (o-o) fs |
|--------------|--------|------------------|------------------|------------------------|
| 25%          | 2%     | 73% [16]         | 60% (YVO$_4$)   | 20%                    |

### Table 2. Harmonics generation efficiency [33].

| SHG of Nd:YAG | THG of Nd:YAG | 4HG of Nd:YAG | SH of Ti:S | TH of Ti:S |
|---------------|---------------|---------------|------------|-----------|
| 80% (KTP)     | 60% (BBO, LBO)| 50% (BBO)     | 31% (BBO) | 24% (BBO) |
Using high-power laser systems, it is shown that normalized performance parameters under consideration are in good agreement with those obtained under significantly less powerful radiation impact with the same specific parameters. Engineering approach makes us to evaluate the wall-plug efficiency of radiation generation with certain parameters (table 1). For a real Nd:YAG ns-laser systems maximum overall optical-to-optical (o-o) conversion efficiencies of sub-Joule fundamental frequency output are specified to be: 64.2% @ 532 nm; 42.8% @ 355 nm; 20% @ 266 nm; 7.1% @ 213 nm [15] (table 2). So we have used these data with 40% wall-plug efficiency estimated to get 1064 nm. Higher wall-plug efficiency (50%) is reported for Yb-doped fiber lasers, having CW or quasi-CW output and often poor beam quality though.

For high energy fs output the following approach can be used: electro-optical (e-o) efficiency of getting pump radiation for fs-oscillator is ca. 4% [16] (since high-quality radiation is needed); radiation for generative amplifier can be estimated as SHG of Nd:YAG 25.6% (e-o); and those normalized by radiation power needed (¼ for seeding and the rest for amplifying giving 20.2% (e-o)), then both converted in Ti:S crystal, resulting in 4% overall efficiency.

Of course, for space systems energy output normalized by mass of the system is also extremely important, but hard to estimated from commercial systems made for operation in the atmosphere. However, this parameter will reduced drastically with pulse length decrease. For reference, fibre coupled diode laser units weigh ca. 0.9 kg/kW [17], collimated diode bars array ca. 0.5 kg/kW. Weight of laser and frequency conversion crystals is negligible as compared to pumping, casing, power and temperature control units. Mass of highly integrated Yb:YAG fibre Coherent HighLight FL1000P unit providing 10 ns, 0.1 J pulses @ 10 kHz (1 kW average power) is ca. 200 kg (cooled by auxiliary water), and wall-plug efficiency is up to 27.7%.

For Al momentum coupling coefficient, we have substituted Joule of laser pulse energy to electric according to recent data for most efficient technologies (figure 1). It can be seen that at nanosecond scale, impact of Nd:YAG fundamental and second harmonics radiation give similar momentum coupling normalized by e-o efficiency. Despite more complicated and less reliable system, using 532 nm radiation could be preferable due-to lower divergence and easier aiming in visual range.

![Figure 1](image-url)  
**Figure 1.** Momentum coupling for Al normalized by e-o optical efficiencies of lasers. Color marks the efficiency open – low (<10%); semi-filled – medium (10-30%); dark – high (>40%). Dots shape shows pulse length: ▼ – fs [20, 21]; ▲ – ps [13]; ● – ns [13, 22-29]; ■ – μs [25, 30]; ♦ – CW [31]; star for ns impact on glass covered target [32]. Marker groups around 1064 nm have lateral shifts for clearer view.
Among 1064 nm impacts, best performance seems to be reached at 20-ps impact, however, data obtained in the same work [13] for ns-pulses are several times higher than the cloud of points obtained from several other papers. It is well known that laser-matter interaction mechanism at ultrashort impact is different to that at short: heat dissipation is minimized and non-thermal mechanisms (e.g., Coulomb explosion) are involved. That leads to the trend shown at figure 2. Glass cover layer (stars at figure 1) gives a very strong advantage (as well as increased specific impulse $I_{sp}$). Such cover layers seems to be the only option for using advantages of combined impact [18, 19]. So it seems to be worth recommending to use second harmonics picosecond pulses and glass covered targets when possible.

![Figure 2](image-url)

**Figure 2.** Dependence of Cu specific ablation energy on laser pulse length (1 – energy required to evaporate Cu from normal conditions $Q_{ev} = 6.17$ MJ/kg; 2 – latent evaporation heat of Cu $Q_{boil} = 4.8$ MJ/kg; dashed line shows the trend; $F_a$ – ablation threshold; $\alpha_{eff}$ – efficient absorption coefficient; $\rho$ – mass density) [34-39].

At space debris laser removal, the microscopic melting and splashing of the resulting melt, which leads to the formation of clouds of new small-size space debris, is also practically not considered, and studied for some specific laser technologies only [40, 41]. However, the amount of this small scale debris will sufficiently depend on pulse duration with least energy spent for melting at ultrashort irradiation.

Momentum coupling coefficient is formed by multiplication of specific ablation rate that changes within $m/E \sim 10^{-4} - 10^{-6}$ g/J range (and usually having an optimum, e.g., see [42]) and mass averaged velocity. Mass averaged velocity of laser ablation plume, which is closely related with specific impulse $I_{sp}$, is strongly dependent on surface state (anodized, brushed or mirror) [23]. It has been shown for Al that mass averaged velocity can change from 1.6 km/s at nanosecond irradiation to 5÷10 km/s at ultrafast impact on brushed targets, for mirror ones velocities estimate was up to 5 times higher (probably affected by crater volume evaluation method errors though). The reason for high $<v>$ form mirror targets is likely not in surface state, but in material layer thickness. It has been shown that for foils and films efficiency of laser impact is higher than for bulk targets due to lower energy losses caused by thermal conduction. Another way to reduce heat losses is using porous media [43].

Of other aerospace materials, for Ti at ultrafast impact $<v> \sim 3÷5$ km/s and thrust efficiency (monochromaticity rate $\mu = <\nu>/<\nu^2>^2 \sim 0.9$ [44]. Much higher values can be found in literature, but
those are usually obtained by time-of-flight methods for ions, so slower neutral fraction is not evaluated. Unlike polymers, it has been shown for metals, that \( <v> \) reaches some limit as fluence increases. In addition to trust efficiency showing the dispersion of velocity vectors, energy efficiency is also evaluated as \( \eta = C_{wfg}/2 \). This is another parameter for further normalization of electro-optical efficiency. Although, there are not so many data published on \( \eta \) (for vacuum especially) as compared to \( C_w \). For Ti at ultrashort impact this parameter reaches 0.8 [42].

3. Possible impact layouts

The first program on laser removal of space debris was proposed in 1989 in the USA (LANL) [45]. Later, the German Aerospace Agency (DLR) demonstrated the possibility of removing most objects up to 10 cm size from the LEO using a space-based laser in several years [46]. Then a significant progress in the development of ground-based laser utilization principles for initiation of space debris surface ablation was achieved in the United States (ORION program – NASA, LANL, LLNL) [47]. For ground-based lasers in 2011, NASA suggested light pressure, not ablation mode, which allows the use of industrial continuous fibre 5–10 kW lasers to deflect the impending collision of objects weighing up to 100 kg for two days [48]. Currently, the use of space-based lasers with lower power requirements is considered for ablation, moreover, without turbulent atmosphere, no complex adaptive optics is needed [49]. Such projects are under development: ICAN [50], L’ADROIT [51], and one more in China [4]. Besides the obvious technical problems, there are also political ones. High-power lasers are dual-use systems (and over 100 kW are considered as combat ones), so subject to restrictions on weapons in space. Impact on satellites, even inactive, but still owned by someone, also requires legal authorization first, in terms of liability in case of damage to third parties in the process of removing.

Estimates made for cost of debris removal by lasers give values 2–3 orders of magnitude less than other methods due to multiple use of one small or non-relocatable system for a number of objects [51, 52] without need for precise approach and contact. The existing level of technology suggests its feasibility in a fairly short time. Powerful ground- or space-based lasers irradiating a number of objects falling within their range periodically, as well as significantly less powerful systems to be attached to the space debris surface directly can be used for exposure [8].

To date, technical possibility of compact solid-state (including fibre) lasers of multi-kW range with average power has been shown [50, 53]. It was announced, that fibre laser is to be installed soon at International Space Station (ISS) [54]. Moreover, solutions of intensive cooling problems for laser active elements and pumping source in space could be simpler than on Earth. However, ground- and space-based high-power laser systems require large capital investments (hundreds of millions of US dollars). It is possible to divide space-based systems into groups of less powerful units located in swarms and acting on space debris objects in parallel, or distributed over near-earth orbits for sequential irradiation. This distribution of power will also contribute to improving the reliability of the system in the context of the practical impossibility of repair and maintenance (with the exception of ISS–based [55]).

Laser impact can be also considered for spacecraft movement correction, e.g., to stop rotation or orbit parameters change. For that, special areas could be provided at spacecraft external surfaces. Even astronaut retrieval system was suggested based on laser propulsion [56].

4. Conclusions

Laser-induced jets could be used both for spacecraft attitude control and space debris removal. For the latter, costs could be significantly reduced as compares to other contact methods, moreover, debris could be accumulated to be used as a fuel source for interplanetary missions using laser thrusters. Despite lower specific impulse than ion thrusters have, laser-induced jet propulsion takes an important niche of moderate thrust and exhaust velocity. Abilities to use any material as a fuel without need for sophisticated storage and supply system, to vary impulse bit within several orders of magnitude range, and to control imparted momentum precisely make laser space debris removal an extremely interesting
option. Technical readiness level of most components needed for such systems makes implementation of those rather realistic in the nearest future. Momentum coupling coefficients normalized by laser output performance, so evaluated for the Joule of energy consumed from the spacecraft power system, to the best of our knowledge, are considered for the first time.

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