Laser-based Space Debris Mitigation in the Low Earth Orbit

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Abstract: Laser ablation is discussed as a method for ground-based orbit modification of space debris in the Low Earth Orbit with the purpose of collision avoidance and debris removal by high energy lasers.
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1. Motivation

The high amount of space debris constitutes a high risk for space missions, in particular in the Lower Earth Orbit (LEO) around 800 km altitude. Beyond residual objects from space missions like, e.g., rocket bodies, inactive payloads or mission-related objects, a multitude of small fragments from explosions and collisions threatens active space missions. While fragments are difficult to detect down to one centimeter object size they still may be lethal for active satellites due to their high velocity. Moreover, due to debris-debris collisions, an exponential increase of debris, referred to as the Kessler syndrome might occur over the next decades [1]. For smaller debris fragments in particular, methods for their removal by orbit modification using remotely induced laser ablation have been proposed in the past [2,3].

2. Laser-ablative Momentum Transfer

When material is irradiated by a pulsed laser, ablation occurs if the laser fluence on the surface exceeds a certain threshold Φ_0. The ablation threshold depends on the target material and the laser wavelength λ and scales with the laser pulse length approximately following $\Phi_0 \propto \sqrt{\tau}$. For metal targets and nanosecond pulses, Φ_0 is in the range of $1 \ldots 10\ J/cm^2$ [4].

The surface material, ablated, e.g., in a vaporization, phase explosion or spallation process, forms a jet which is essentially perpendicular to the target surface and induces a recoil to the remaining target. The imparted momentum p can be quantified by the so-called momentum coupling coefficient $c_m = p/E$ where E is the incident laser pulse energy. Momentum coupling typically amounts from $1 \ldots 300\ \mu Ns/J$ depending on material and laser irradiation parameters λ, τ, Φ [5]. With respect to space debris materials in particular, we have shown experimentally that momentum coupling in the range of $10 \ldots 20\ \mu Ns/J$ can be achieved for aluminum, polyimide and solar cell material using nanosecond pulses ($\tau = 8\ ns, \lambda = 1064\ nm$) focused on the target with fluences in the range of $4 \ldots 12\ J/cm^2$.

In the case of the targeted space debris fragments from collisions and explosions rather irregularly shaped objects prevail which can be classified as, e.g., flat plates, curled plates, flakes, rods, nuggets and other geometries [6]. Here, assessment of momentum coupling requires consideration of all irradiated surface elements $dA_i(\vec{r}_i)$ of the target where the overall momentum is summed up over all irradiated surface elements, $\vec{p} = \sum_i \vec{p}_i(\vec{r}_i)$, with $\vec{p}_i(\vec{r}_i) = -c_m\big(\Phi(\vec{r}_i), \vartheta(\vec{r}_i)\big) \cdot \Phi(\vec{r}_i) \cdot dA_i(\vec{r}_i) \cdot \cos\vartheta(\vec{r}_i) \cdot d\hat{n}(\vec{r}_i)$ where ϑ is the laser incidence angle and $\hat{n}$ is the local surface unit normal vector. This approach has been implemented in our numerical code EXPEDIT for the calculation of imparted momentum by laser ablation for arbitrarily shaped objects [7].

EXPEDIT has been validated experimentally using differently shaped targets of various materials and a few centimeters size under vacuum in a drop experiment representing thus a setting similar to in-orbit conditions [8]. Transfer of coaxial, lateral and rotational momentum from a single laser pulse outshining the target with approximately 80 J pulse energy yielding fluences of up to $10\ J/cm^2$ has been investigated. Comparison with EXPEDIT has shown a good agreement of numerical data and experimental results. Moreover, momentum imparted from the laser pulse yielded velocity increments in the range of $\Delta v \approx 0.25 \ldots 1.5\ m/s$ for metal targets.

3. Laser-ablative Orbit Modification

The feasibility of applying a meaningful velocity increment to a space debris object mainly depends on its characteristic ratio A/m where A is the target's cross-sectional surface area being available for laser irradiation and m is the mass of the target. With an area-to-mass ratio in the range of $A/m \approx 0.1 \ldots 1\ m^2/kg$ debris fragments in the size range of a characteristic length of $L_c = 1 \ldots 10\ cm$ are well-suited targets for laser-based momentum transfer [6].

In this regard, laser-ablative collision avoidance is proposed in order to reduce the risk of the generation of additional space debris in orbit and for the protection of active satellite missions. For this purpose, a small decrease of the debris velocity by $\Delta v = 1\ cm/s$ would already result in a displacement of $\Delta x = 2.5\ km/day$ in LEO [9]. In this regard, it can be seen from our above-mentioned experimental findings that collision avoidance in orbit can be achieved by laser ablation if the target surface is irradiated at an appropriate laser fluence.

Our previous studies in the European project CLEANSPACE have shown that applying high laser fluence from ground-to-orbit through the turbulent atmosphere over such large distances is feasible in principle [10]. However, depending on the laser transmitter aperture as well as on the performance of adaptive optics for compensation atmospheric turbulence, a laser spot size of approximately 0.5 m up to a few meters can be expected. Hence, in order to achieve the required laser fluence at the debris target, pulse energies of $E \approx 10 \ldots 200\ kJ$ would be needed. Whereas power beaming of such high pulse energies is technically feasible in general, as shown in our recent work on coherent beam combining [11], it should be noted that for collision avoidance pure photon pressure might be suitable as well [9]. In this case, the absence of a threshold fluence or intensity allows for the employment of commercially available high power lasers. However, since momentum coupling amounts to $c_m \approx 7\ nNs/J$ at most, a global network of laser stations is required for irradiation during several station transits.

Space debris collision avoidance using a single laser pulse would be useful to save satellite propellant for station-keeping and, moreover, would contribute to delay the Kessler syndrome. In contrast, repetitive irradiation of space debris during several laser station transits might yield an overall velocity increment that is even high enough to remove debris fragments from LEO. Given $\Delta v \approx 150\ m/s$, the orbit's perigee would be lowered sufficiently enough for eventual burn-up of the target in Earth's upper atmosphere. For the laser-based engagement, however, laser-matter interaction has to be adapted carefully to the target material in order to avoid thermo-mechanical target disintegration.

Ongoing work in this field at our institute cover the topics of debris detection and its laser-based ranging, high energy laser development, coherent beam combining, adaptive optics, laser safety, remote reconnaissance of debris material and shape, laser-debris interaction as well as orbit propagation for predictive avoidance of collateral damage to active satellites.

4. References

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