Ablative collision avoidance for space debris in the Low Earth Orbit by a single multi-kJ pulse from a ground-based laser

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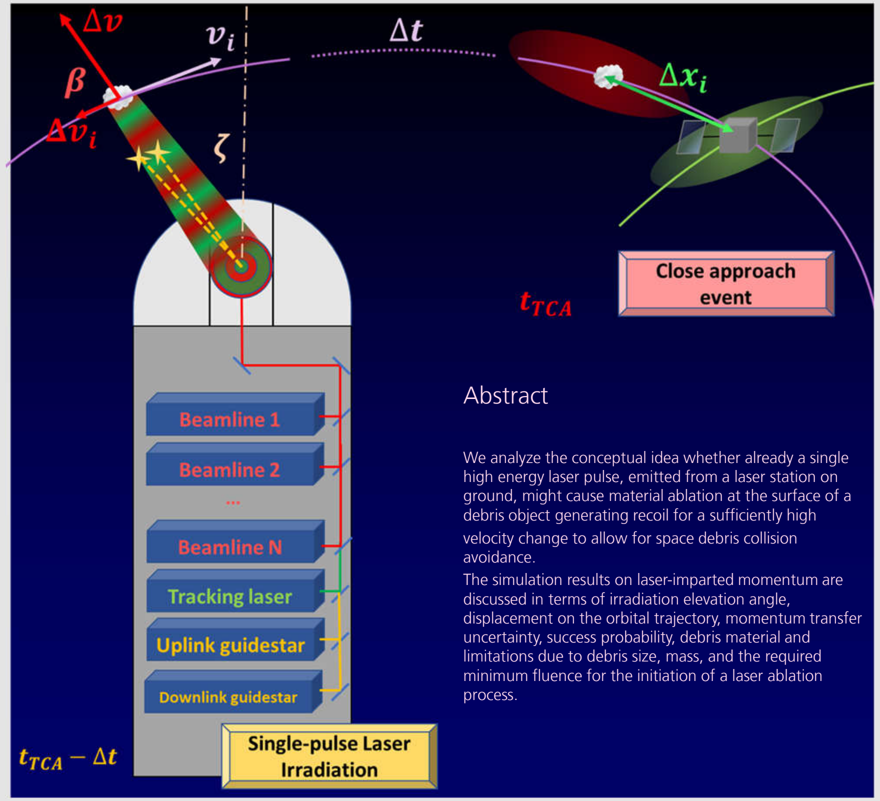


Abstract

We analyze the conceptual idea whether already a single high energy laser pulse, emitted from a laser station on ground, might cause material ablation at the surface of a debris object generating recoil for a sufficiently high velocity change to allow for space debris collision avoidance.

The simulation results on laser-imparted momentum are discussed in terms of irradiation elevation angle, displacement on the orbital trajectory, momentum transfer uncertainty, success probability, debris material and limitations due to debris size, mass, and the required minimum fluence for the initiation of a laser ablation process.

Conceptual view of laser-based collision avoidance using a ground station operating 1-2 days prior to the time of closest approach. Laser power beaming is assisted by adaptive optics and laser ranging. Laser-induced momentum causes a decrement $Δv_i$ in the in-track velocity of the debris object yielding a displacement $Δx_i$ on its trajectory at the time of closest approach that enables collision avoidance. The objects' covariances are indicated by the ellipsoids shown in the close approach event.

Ground-station configuration

Laser pulse energy:	76 kJ (4 NIF beamlines)
Laser pulse duration:	5 ns
Laser wavelength:	1053 nm (near-infrared)
Transmitter aperture:	2.5 m
Tracking precision:	0.1 arcsecs
Pointing precision:	0.01 arcsecs
Adaptive optics:	300 actuators, 2 laser guidestars

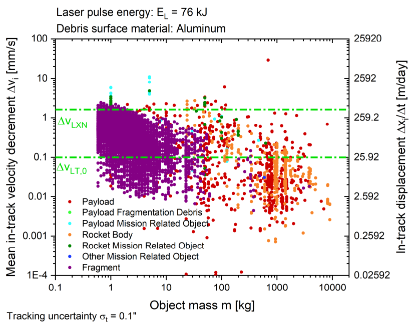
Debris operational orbital regime (OOR)

606 rocket bodies
770 payloads
90 mission-related objects
7636 fragments

Altitude:	579 km – 1179 km
Eccentricity:	0.0 – 0.2
Inclination:	65° - 115°

Simulation method

- Computation of turbulence compensation for laser power beaming using adaptive optics
- Numerical simulations based on 9101 debris targets
- Simplified geometries using ESA DISCOS data on shape, mass, dimensions and cross-sectional area
- Ray-tracing based simulation code EXPEDIT for the computation of recoil from laser-induced surface ablation
- Simulation of laser-matter interaction based on experimental data for Al, Cu, and stainless steel as generic sample materials
- Consideration of random orientation and beam pointing jitter by Monte Carlo sampling



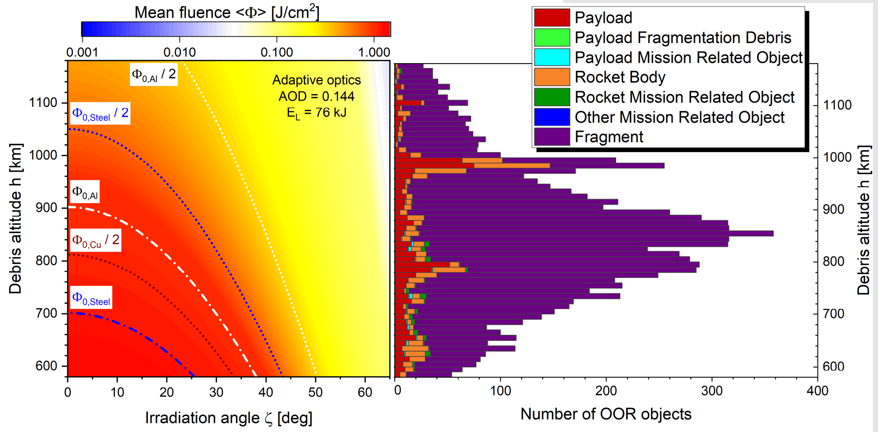
Mean in-track velocity decrement from laser-ablative recoil under irradiation with a ground-based laser site emitting a single laser pulse of 76 kJ pulse energy. Target material: aluminum (generic). Results have been derived from Monte Carlo simulations averaging over samples with random target orientation and beam offset in laser pointing using a tracking uncertainty of 0.1 arcsec. For each target the optimum zenith angle is chosen where the in-track velocity decrement $Δv_i$ reaches its maximum value.

Results

Laser-ablative momentum generation is limited for lower fluences by the ablation threshold and small momentum coupling in the vaporization regime, resp.

Hence, laser beam quality constraints demand for moderate distances between ground station and debris, which makes laser-ablative momentum transfer more effective for LEO objects at smaller altitudes.

Low beam pointing elevations are beneficial to yield high in-track deceleration, but detrimental in terms of laser fluence.



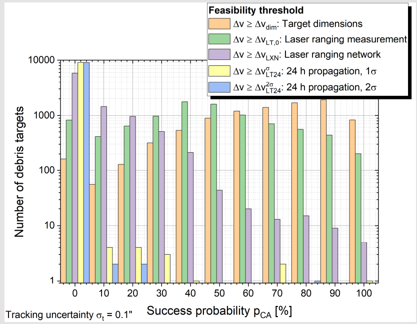
Mean fluence in orbit using adaptive optics and four laser beamlines (overall 76 kJ laser pulse energy), together with debris population in the targeted orbital operational regime (OOR) as a function of mean orbital altitude. Threshold fluences for laser ablation are marked with dash-dotted lines in the fluence graph. Dotted lines indicate where 50% of the threshold fluence is surpassed which is equivalent to the ablation threshold in the center of a spot with Gaussian fluence distribution.

Debris in-track displacement

Depending on target material, size and mass, velocity changes in the order of 10 µm/s to 1 mm/s can be expected which corresponds to a displacement of ~2.5 m to ~250 m one day after the laser engagement.

Momentum transfer on smaller debris objects can be less efficient due to outshining losses within a comparably large laser spot.

Beam pointing jitter and sparse information on target orientation yield large scatter in the prediction of momentum. Related success probabilities for collision avoidance have been derived from statistics over a multitude of Monte Carlo samples.



Histogram on success probability of single-pulse (76 kJ) laser-based collision avoidance for different feasibility criteria, quantify by the debris' in-track displacement that is obtained 24 hours after the laser irradiation:

$Δv_{dim}$ – The target is displaced by its maximum extension X.

$Δv_{LT}$ – The velocity change amounts to100 µm/s which equals a displacement by 25.9 m after 24 hours of further orbital motion in LEO.

$Δv_{LXN}$ – The laser-induced change of in-track velocity is 1.6 mm/s giving a displacement of 414 meters after 24 hours which is in the order of the average 2-sigma uncertainty of orbital data from a small-sized global laser ranging network.

$Δv_{LT24}$ – The laser-induced velocity change yields an in-track displacement which is in the order of the orbital data uncertainty 24 h after a laser ranging measurement (approx. 300 – 700 meters, 1-sigma).

Summary

A single multi-kJ laser station might constitute an attractive stand-alone alternative to a network of high-power CW laser stations. Alternatively, it might serve as a useful supplementary device in a hybrid (CW + pulsed) framework for collision avoidance.

Responsible use and conceivable misuse should be addressed by global governance regulations.

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