Space Sustainability by Laser Propulsion
DLR Research from Launch to Post-Mission Disposal

Stefan Scharring, Raoul-Amadeus Lorbeer
German Aerospace Center (DLR), Institute of Technical Physics

ESA IP-CCI Workshop on Innovative Propulsion
ESA ESTEC, Noordwijk, The Netherlands – 29 June 2023

DLR

Laser Propulsion Studies
@ DLR Institute of Technical Physics

Spacecraft Propulsion Concepts

- Laser-ablative micropropulsion
- Remotely powered orbital transfer
- Remotely powered launch

Debris Propulsion Applications

- Collision avoidance by photon pressure
- Laser-ablative collision avoidance
- Laser-ablative debris removal by re-entry

Sustainability Issues of Laser Propulsion

DLR

Spacecraft Propulsion Concepts

	Eco-friendly exhaust	Propellant reduction
▪ Laser-ablative micropropulsion	✓	x
▪ Remotely powered orbital transfer	✓	✓
▪ Remotely powered launch	✓	✓

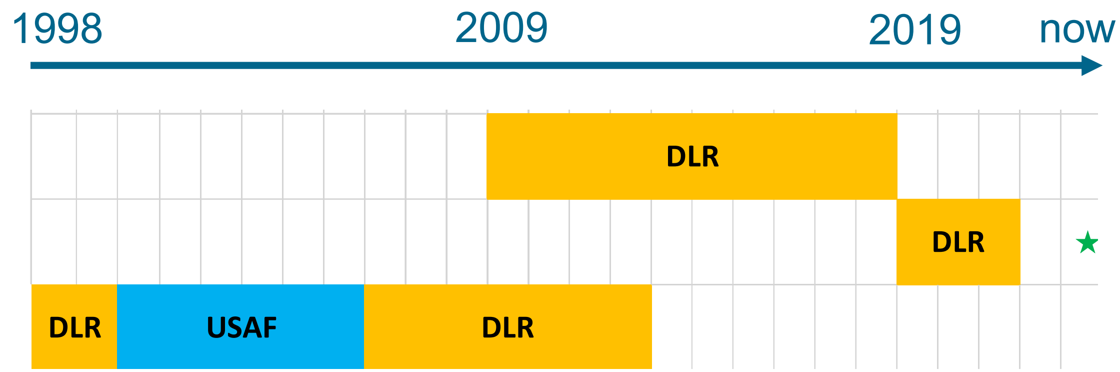
Debris Propulsion Applications

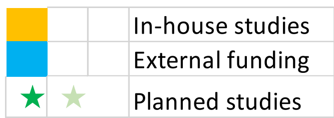
	Risk mitigation	LEO protection
▪ Collision avoidance by photon pressure	✓	x
▪ Laser-ablative collision avoidance	✓	x
▪ Laser-ablative debris removal by re-entry	✓	✓

Activity status

Spacecraft Propulsion Concepts

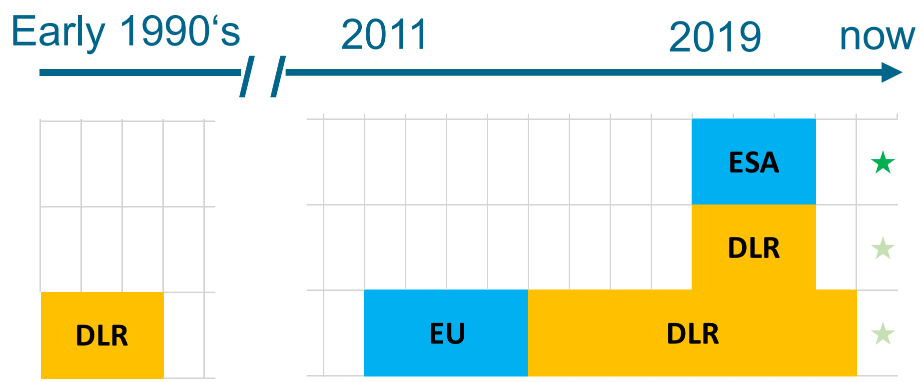
- Laser-ablative micropropulsion
- Remotely powered orbital transfer
- Remotely powered launch





Debris Propulsion Applications

- Collision avoidance by photon pressure
- Laser-ablative collision avoidance
- Laser-ablative debris removal by re-entry

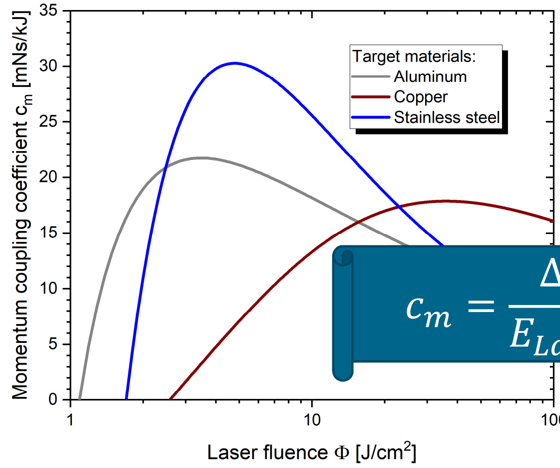


Micropropulsion w/o moving Components

Target applications

- Precise attitude control
- Replacement / complement for electric propulsion

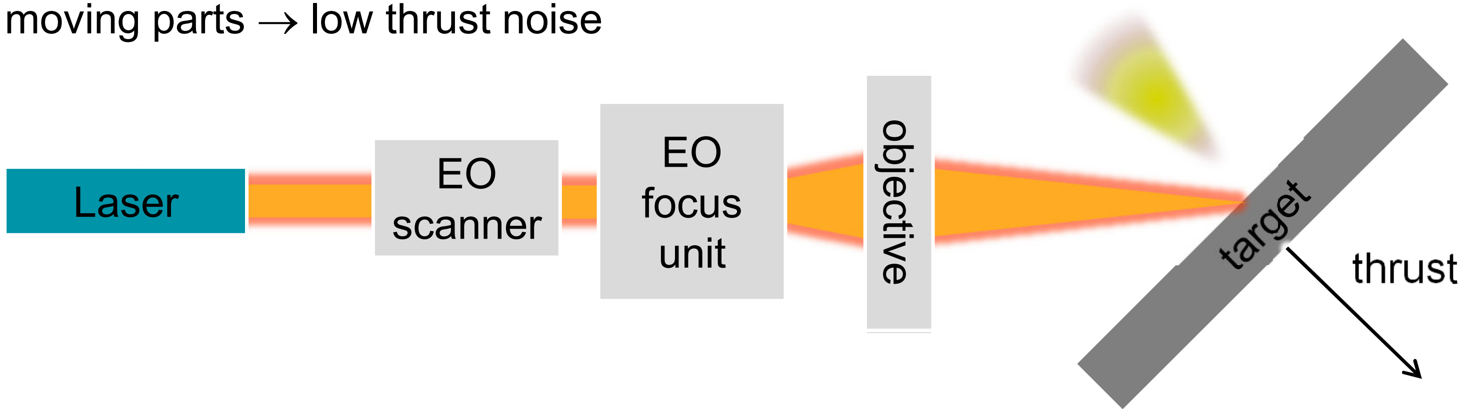
- Very small impulse bits
- Laser pulse rate → thrust level



No moving parts → low thrust noise

DLR heritage

- Small (~µN) thrust measurement
- Thrust noise evaluation
- Design for micro thruster



Onboard laser → NOT remote propulsion

S. Scharring et al., "The MICROLAS concept: precise thrust generation in the micronewton range by laser ablation," in IAA Book Series on Small Satellites 1(6), 27 - 34 (2016)

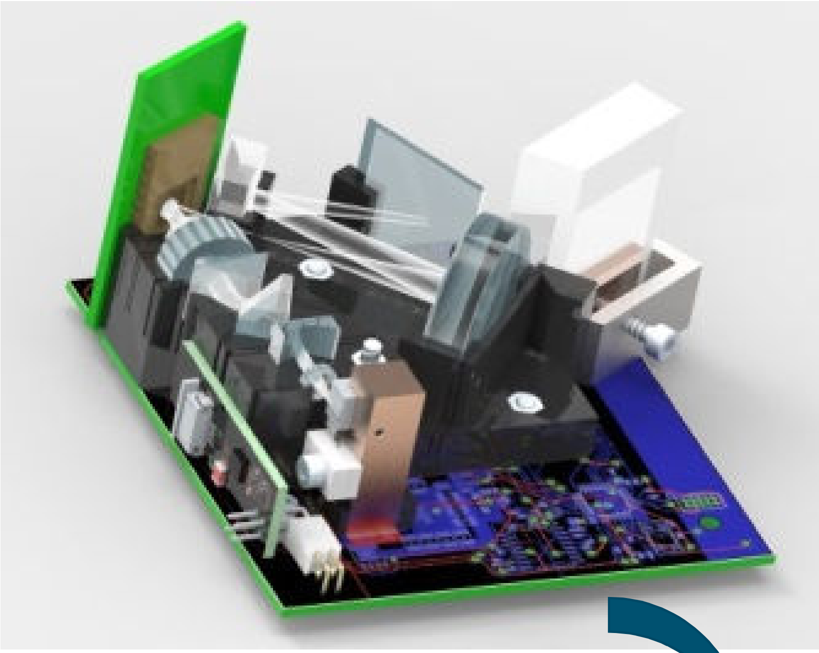
Micropropulsion w/o moving Components

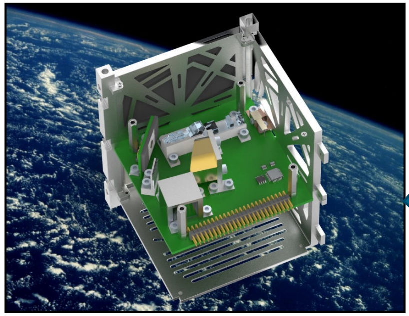
State of the art

- Demonstration module for micro thruster
  - 180 mW laser diode (10 µs pulse, 1 kHz)
  - 2D MEMS scanner → residual thrust noise
  - Liquid lens (electro-optical)
  - Propellant: graphite
  - USB-powered

Development needs

- Maturation of core technologies for in space use:
  - ns-pulsed Laser
  - Optical Scanner
  - Optics cleaning





10 x 10 x 5 cm³

Toni Bauer et al., USB-powered technology platform for laser ablative thrust generation, OSA Continuum 4, 1304-1315 (2021) , https://doi.org/10.1364/OSAC.419481

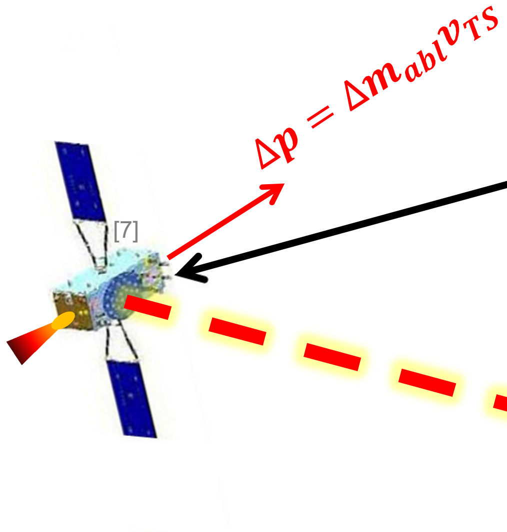
Post-mission Disposal powered from Ground

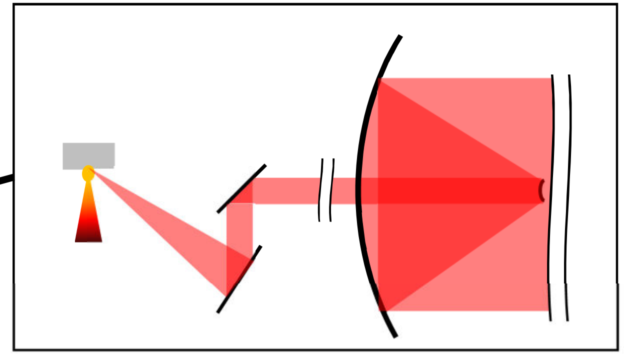
Target applications

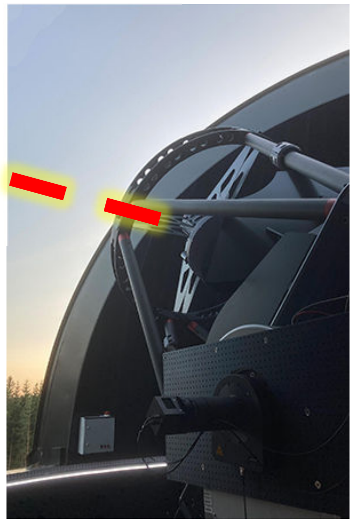
- Deorbiting of space craft post mission.
- Business case: Laser-based deorbiting service

DLR heritage

- Conceptual studies comprising:
  - Power to thrust converter
  - Power beaming
  - Orbital maneuvers





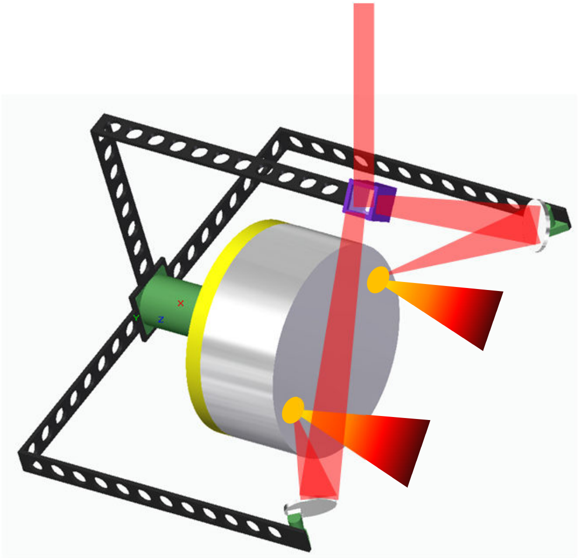


Scharring, S. et al., Method for planning a satellite maneuver, patent WO 2022/089979 A1

Post-mission Disposal powered from Ground

State of the art

- Detailed calculations and concepts for
  - Power to thrust converter
  - Power beaming
  - Orbital maneuvers



Development needs

- Technologies for ground Station:
  - Laser-system, adaptive optics, large aperture power-beaming
- Technologies on S/C:
  - Large aperture laser-power receiver, beam steering, power to thrust conversion

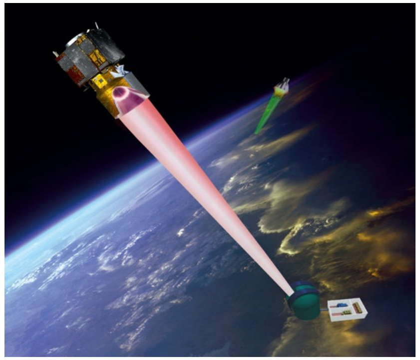
Scharring, S. et al., Method for planning a satellite maneuver, patent WO 2022/089979 A1

Laser Lightcraft: Launch by Photons + Air

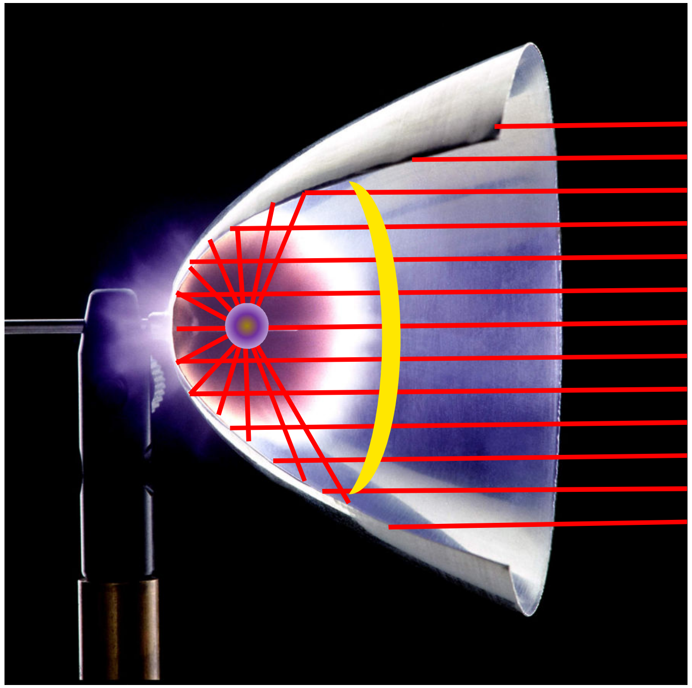
„$I_{sp} \rightarrow \infty$"

Target applications

- Picosat launchers
- Ground station for sustainable supply of propulsive energy
- … or from space-based station:
  - Sample return missions (tractor beam)
  - In-orbit logistics

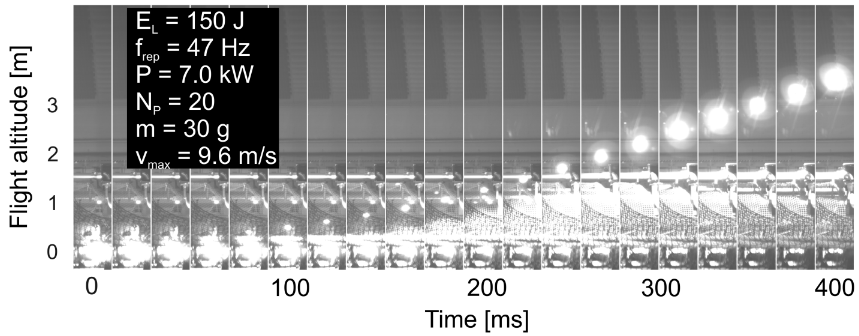


H.-A. Eckel et al., Concept for a Laser Propulsion Based Nanosat Launch System, AIP Conf. Proc. 702, 263 – 273 (2004), https://doi.org/10.1063/1.1721006



DLR heritage

- Parabolic lightcraft with ignition and steering device
- CO_2 high energy laser experiments: plasma diagnostics, impulse pendulum, lab flight experiments
- Beam-riding analysis

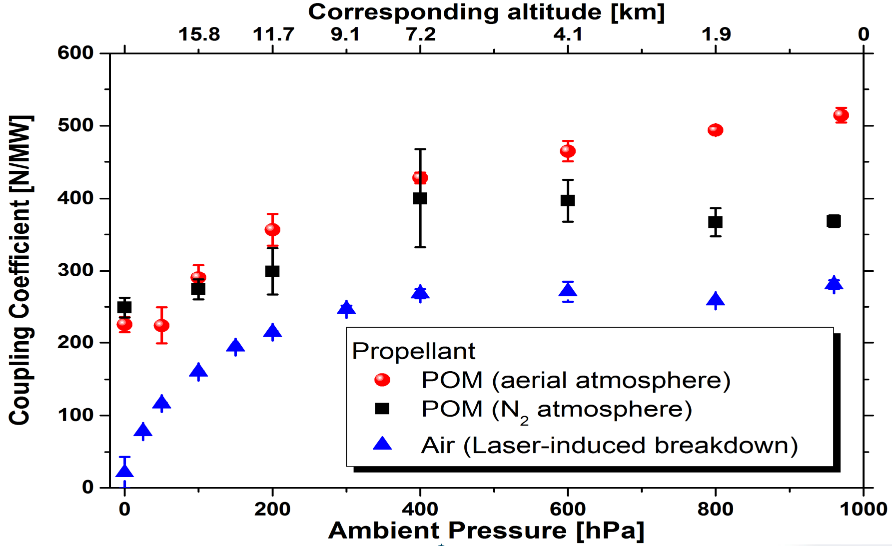


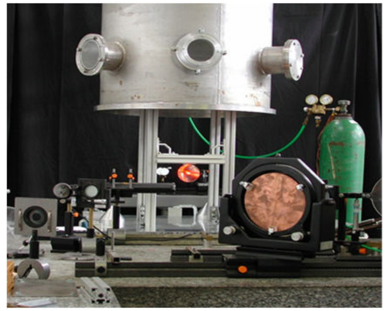
S. Scharring, Impulse analysis of air-breathing pulsed laser propulsion for space applications using a reflective nozzle (in German), PhD thesis, University of Stuttgart (2013) , https://elib.dlr.de/82712/

Picosat Launchers with laser-ablative propellant

State of the art

- Free flight in the laboratory (8 m) with air breakdown (no propellant)
- 10 kW pulsed laser → 30 g vehicle
- Beam-riding constraints identified
- Analysis of laser ablation & detonation



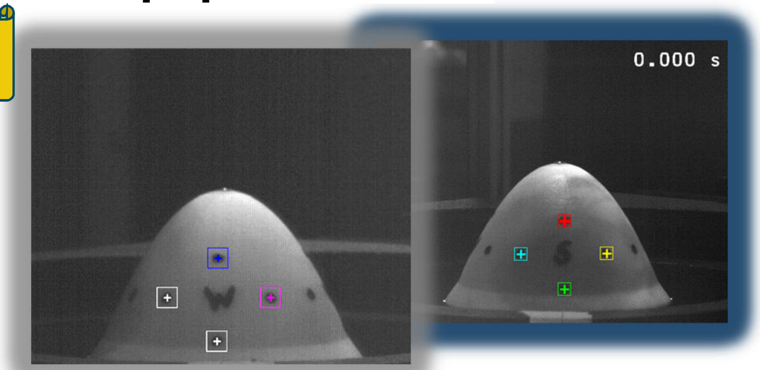


W.L. Bohn and W.O. Schall, Laser Propulsion Activities in Germany, AIP Conf. Proc. 664, 79 – 91 (2003), https://doi.org/10.1063/1.1582098

Development needs

$$m_{payload}/P_{Laser} \approx 1\,kg/MW$$

- High energy ground laser (10 – 100 kJ, 10 – 1000 Hz, near IR)
- High energy transmitter + adaptive optics
- Beam riding design + steering loop
- Propellant optimization



Front view

Side view

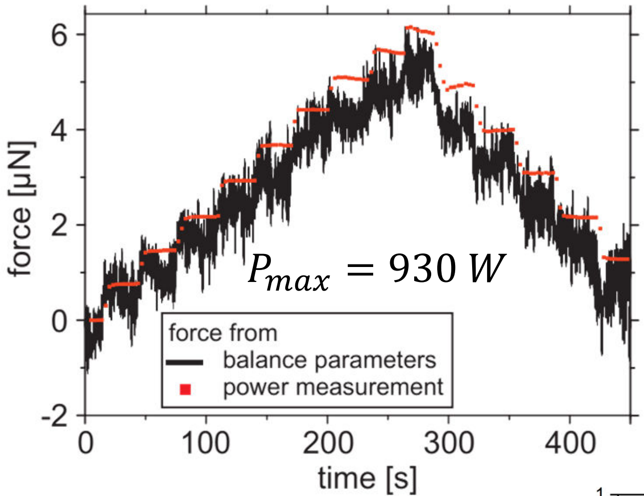
S. Scharring et al., Beam-Riding Analysis of a Parabolic Laser-thermal Thruster, AIP Conf. Proc. 1402, 115 – 131 (2011), https://doi.org/10.1063/1.3657021

LEO Space Debris Nudging by Photon Pressure

Target applications

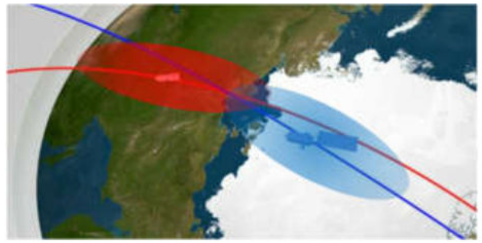
Collision avoidance:

- Debris vs. debris
- Deb. vs. non-maneuvrable S/C
- Service for propellant saving



S. Karg et al., Laser Propulsion Research Facilities at DLR Stuttgart, HPLA 2014, https://elib.dlr.de/89162/

$$c_m \approx 5\ \mu N/kW$$

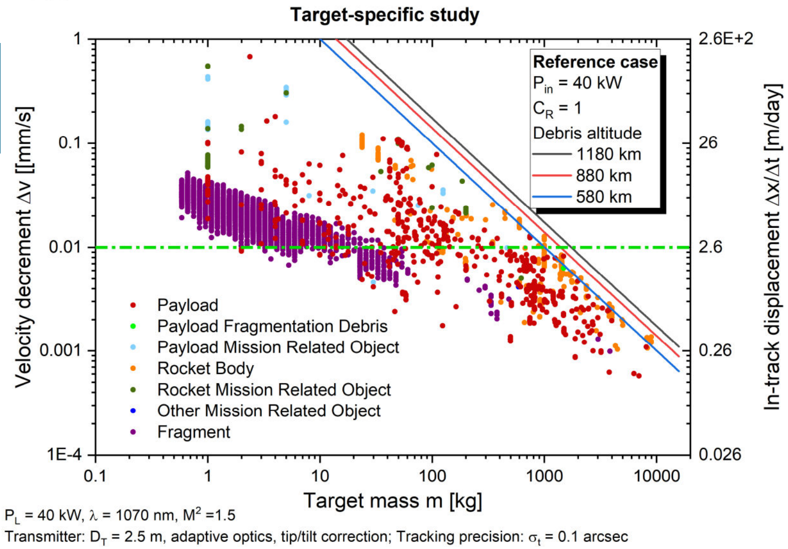


Collision probability from covariance overlap

Image: ESA / DLR

DLR heritage

- Laser ranging and lightcurve analysis
- Development of high power solid-state lasers
- Measurement of photon pressure at kW laser power level
- Light force raytracing computations for arbitrarily shaped targets
- Network analysis for laser tracking and momentum transfer (LTMT) including weather constraints
- High-level LTMT station design
- Prime of ESA Phase 0 Study (2019 – 2021)



S. Scharring et al., LARAMOTIONS: a conceptual study on laser networks for near-term collision avoidance for space debris in the low Earth orbit, Appl. Opt. 60(31), H24-H36 (2021), https://doi.org/10.1364/AO.432160

Space Debris Nudging by a LTMT Station Network

$\Delta x/\Delta t \approx 2.6\ m/d$ from $\Delta v = 10\ \mu m/s$

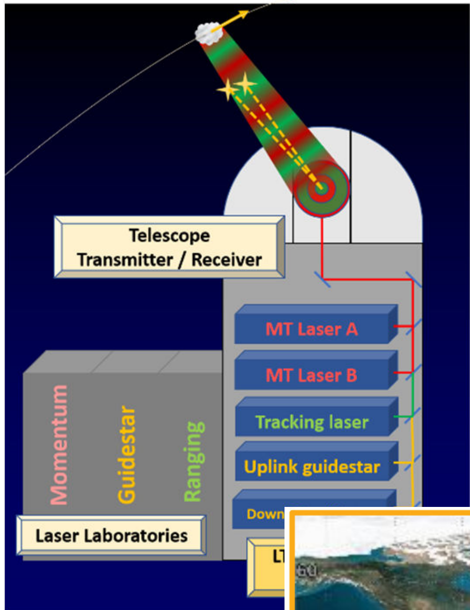
State of the art

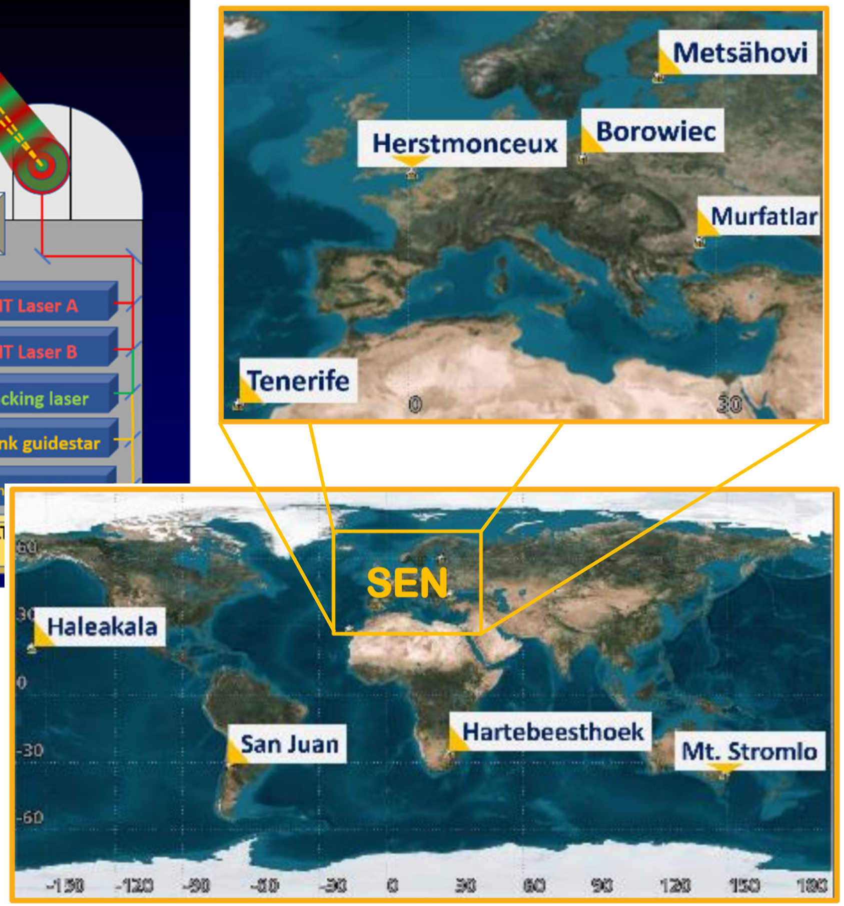
Feasible station requirements found:

- 0.1“ precision tracking with adaptive optics
- Adaptive focusing supported by laser ranging
- 40 kW by beam combining of solid-state lasers
- 2.5 m transmitter
- 0.1“ pointing precision

Development needs

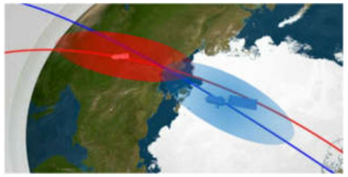
- High power beam combining
- High power adaptive optics
- High precision tracking and pointing
- Risk mitigation (thermal, reflections, political)





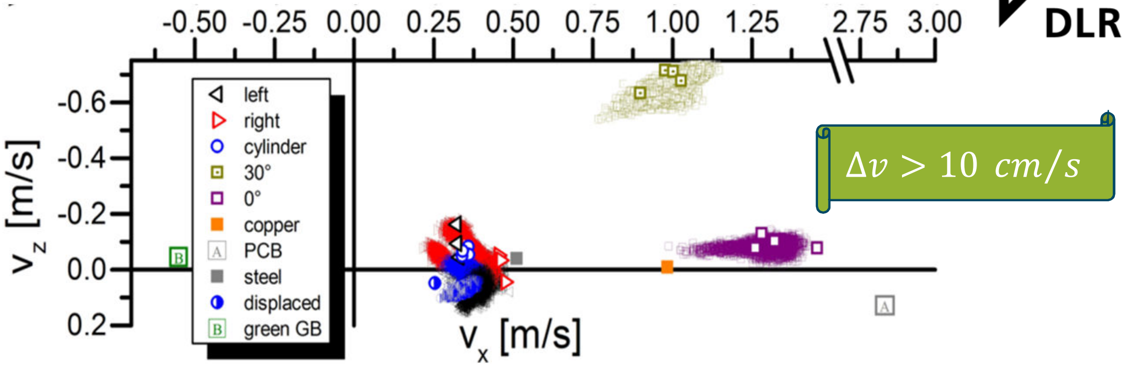
E. Cordelli et al., Ground-based laser momentum transfer concept for debris collision avoidance, J. Space Saf. Eng. 9(4), 612-624 (2022), https://doi.org/10.1016/j.jsse.2022.07.004

Ground-based Collision Avoidance by a few Laser Pulses



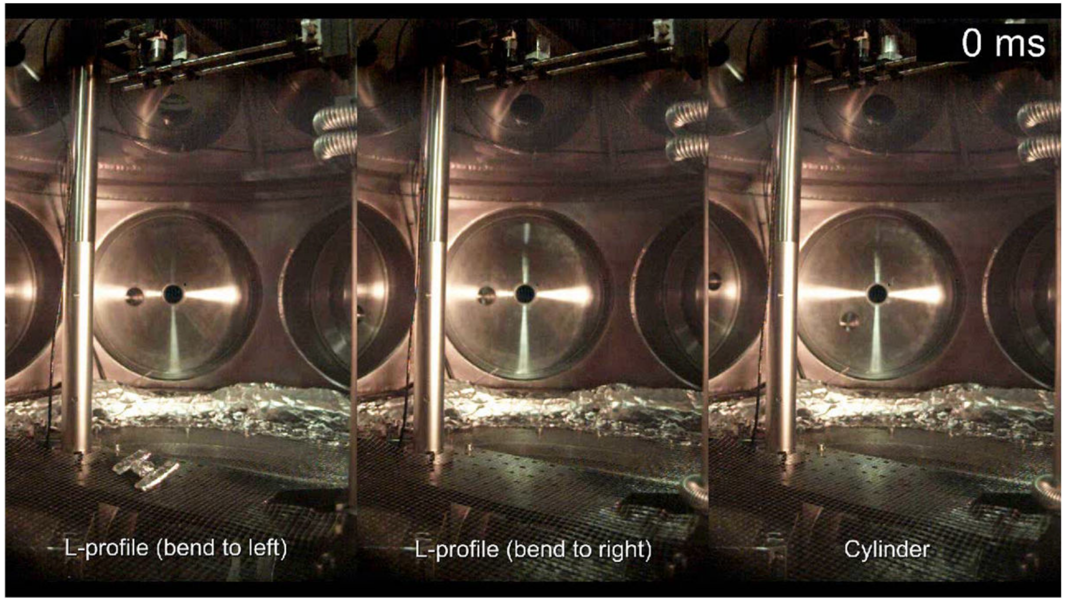
Target applications

- Collision avoidance:
  - Debris vs. debris
  - Debris vs. non-maneuvrable satellites
  - Service for propellant saving
  - Supplement / upgrade for LTMT by photon pressure



DLR heritage

- Single pulse experiments on laser-induce momentum and heat to cm-sized targets
- FEM and raytracing simulations on thermo-mechanical laser-matter interaction
- Simulations of atmospheric beam propagation and turbulence compensation



Laser pulse energy: 80 J, single pulse (nHelix, GSI Darmstadt)

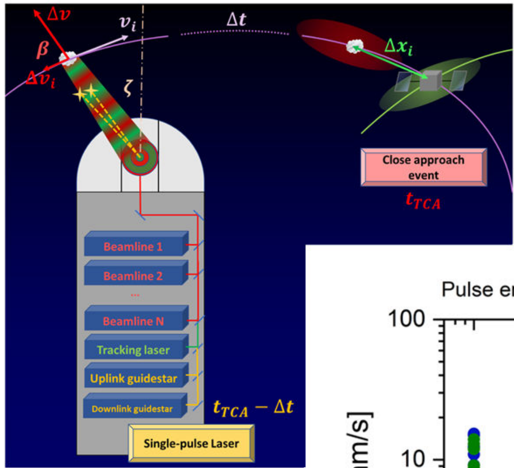
R. Lorbeer et al., Experimental verification of high energy laser-generated impulse for remote laser control of space debris, Sci. Rep. 8: 8453 (2018), https://doi.org/10.1038/s41598-018-26336-1

Ground-based Collision Avoidance by a few Laser Pulses

DLR

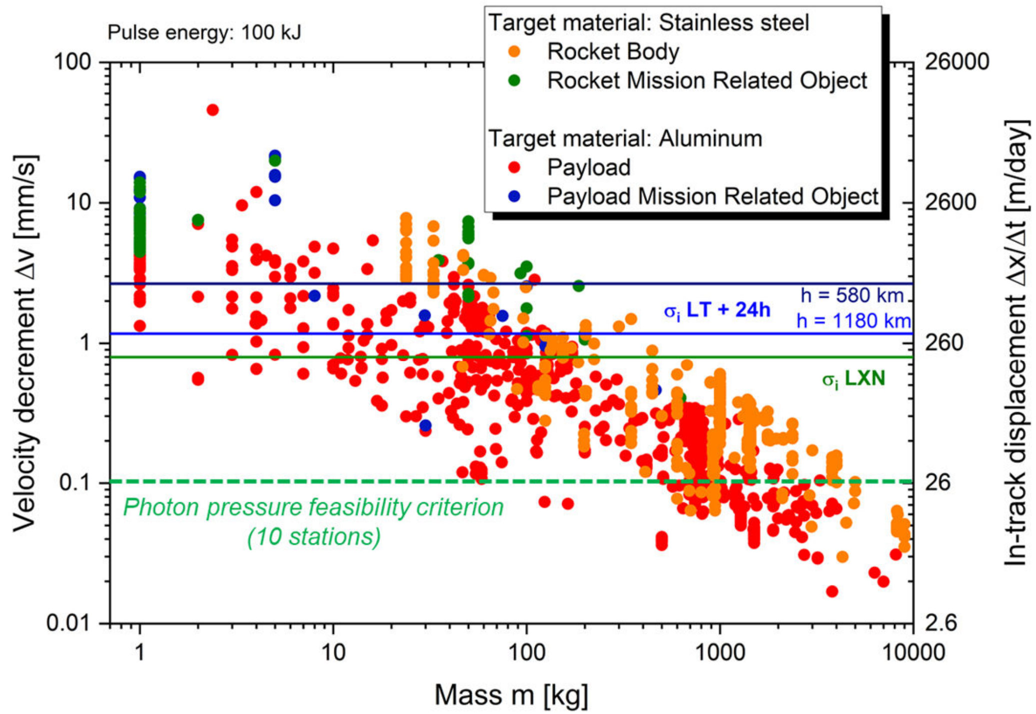
State of the art

- Experimental proof-of-principle in vacuum drop experiment
- Analysis of adaptive optics configuration to achieve relevant fluences in LEO



Development needs

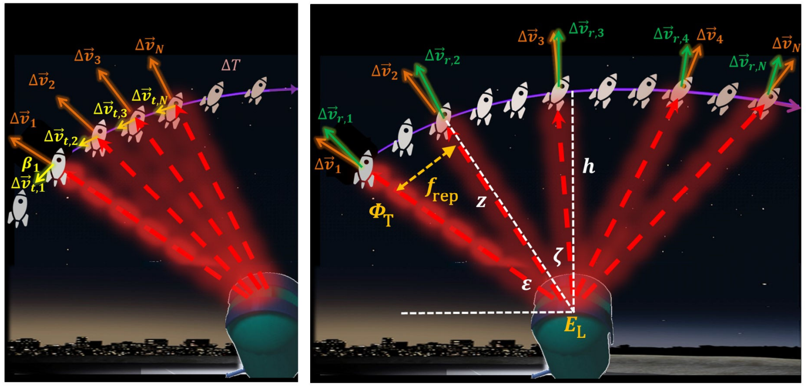
- Adaptation of kJ beamline technology from inertial fusion (or coherent beam coupling)
- High energy transmitter with adaptive optics



Scharring, S. et al., Ablative collision avoidance for space debris in the Low Earth Orbit by a single multi-kJ pulse from a ground-based laser, 2021 AMOS Conf. Proc., 1679–1692, https://elib.dlr.de/145009/

De-orbiting of small Space Debris

$h_{perigee} \rightarrow 200\ km$

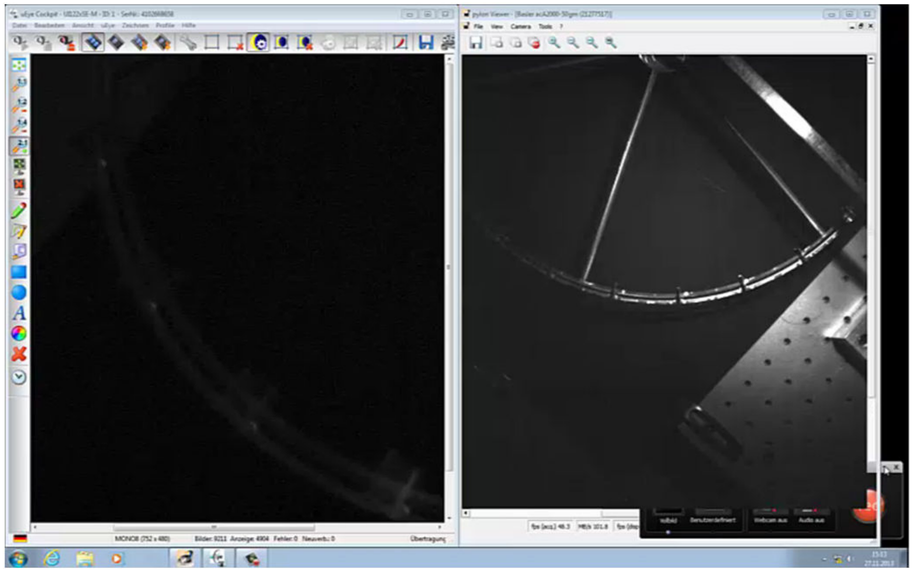


Target applications

- Removal of debris fragments
- Collision avoidance as integrated business case

DLR heritage

- Development of pulsed high energy solid-state lasers
- Research on coherent beam coupling
- Laser-ablative thrust measurements for space debris materials
- Simulation of laser-momentum coupling to arbitrarily shaped targets
- Propagation of laser-modified orbits
- Analysis of operational safety (thermo-mechanical, legal…)



Laser power: 33 W, Thrust: 700 µN

B. Esmiller et al., Space debris removal by ground-based lasers: main conclusions of the European project CLEANSPACE, Appl. Opt. 53(31): I45 – I54 (2014), https://doi.org/10.1364/AO.53.000I45

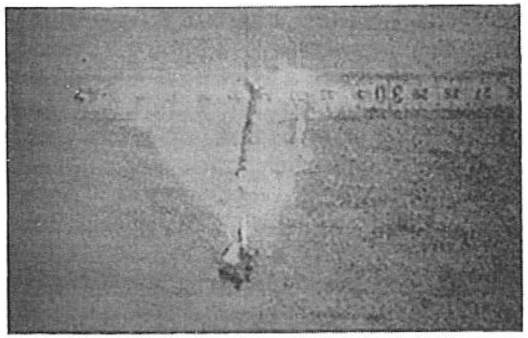
De-orbiting of small Space Debris

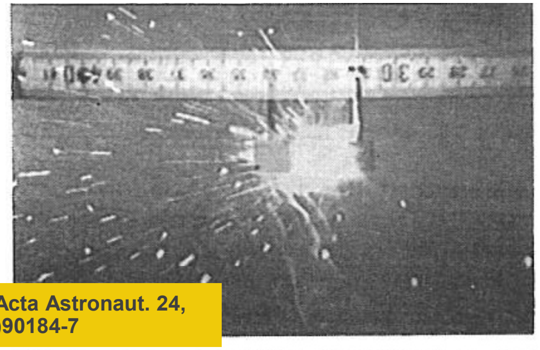
State of the art

- Detailled analysis on momentum coupling
- Identification of thermal constraints
- Pulsed laser sources on the 1 Joule level
- Coherent coupling of a few laser emitters

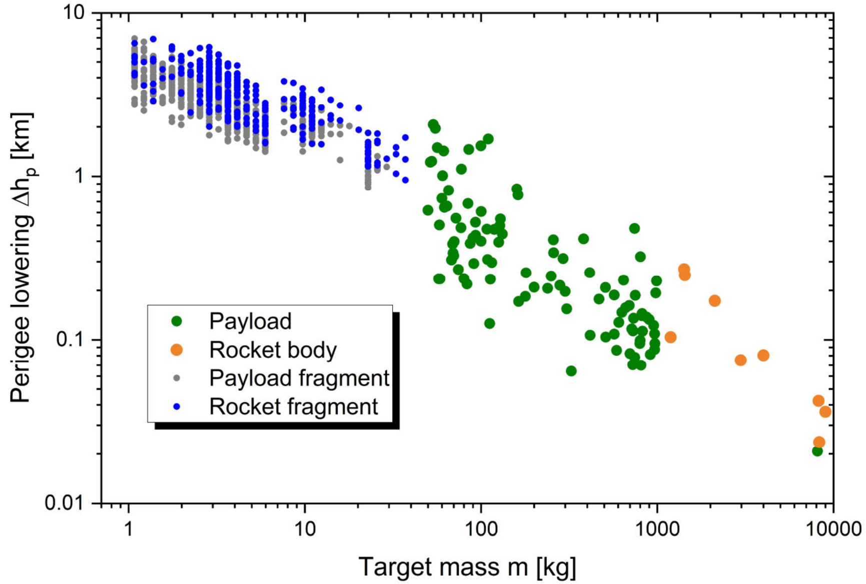
Development needs

- Predictive avoidance for orbit modification
- Debris reconnaissance for target selection/exclusion
- Pulsed laser sources on the 10 – 20 J level
- Coherent coupling of a few thousand laser emitters
- Transmitters and adaptive optics for high pulse energies

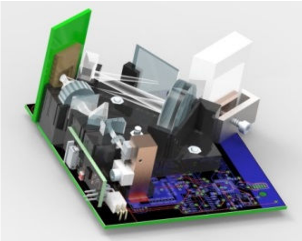
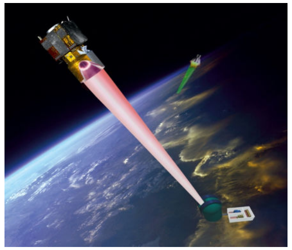
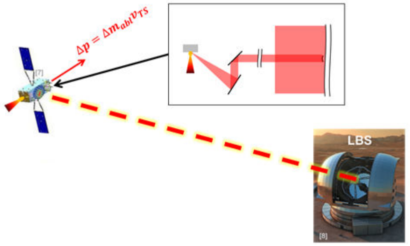
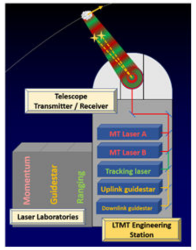
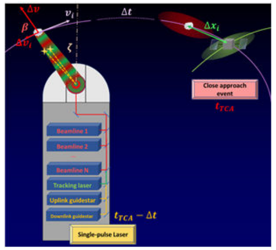
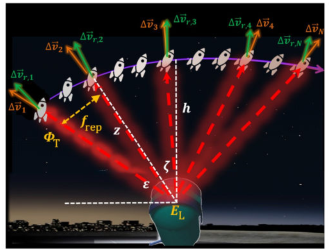




W. Schall, Orbital debris removal by laser radiation, Acta Astronaut. 24, 343–351 (1991), https://doi.org/10.1016/0094-5765(91)90184-7



S. Scharring and J. Kästel, Can the Orbital Debris Disease Be Cured Using Lasers?, Aerospace (in review), https://www.preprints.org/manuscript/202305.1802/v1

Thank you for your kind attention

Lasers and Space

The things we see are the result of our past,
but the way we act is the result of our future.

Gravitational lensing smiley, credit: NASA & ESA under CC BY 4.0 license