Interaction constraints for laser-based removal of space debris

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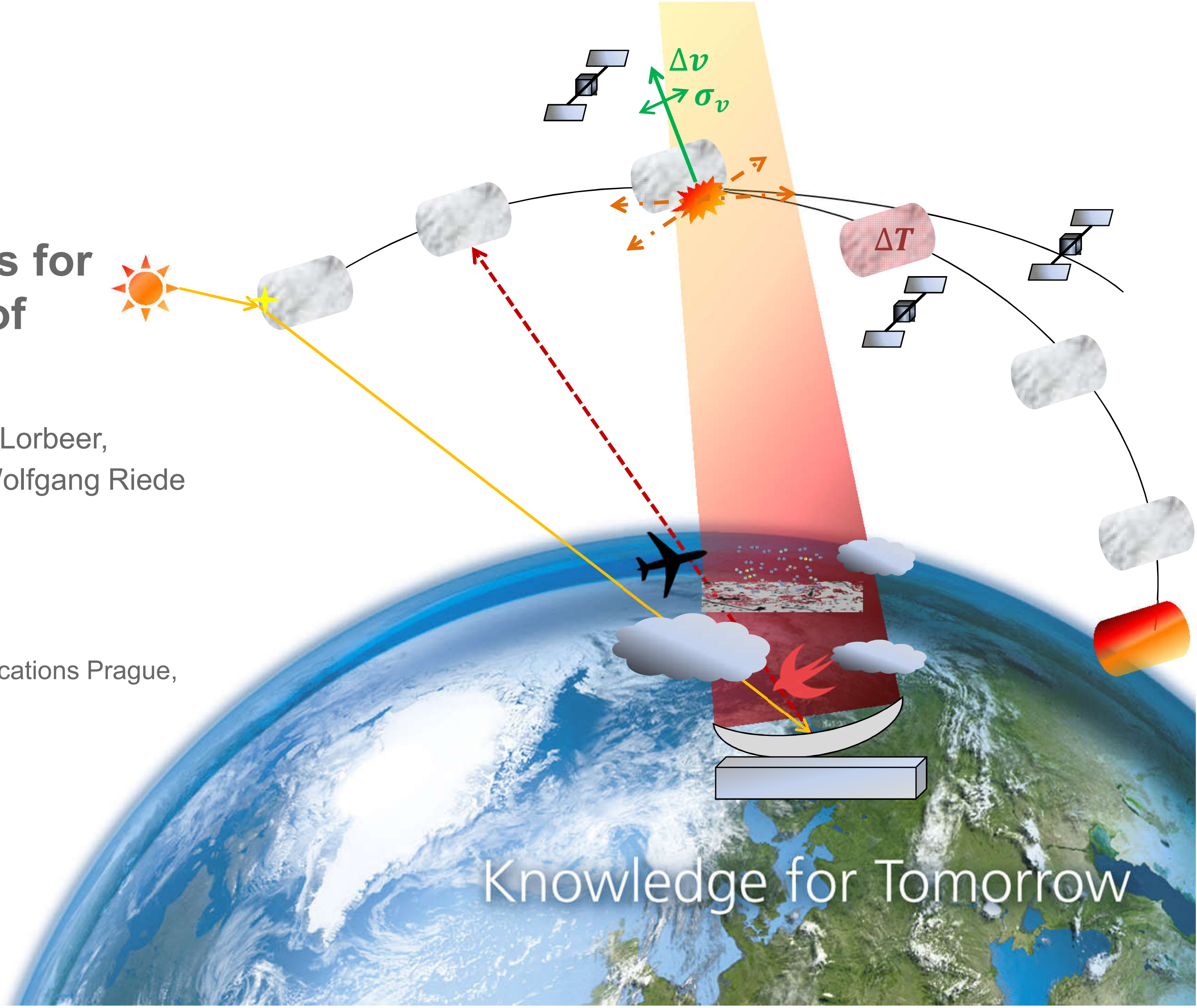
HiLase Workshop on Laser Space Applications Prague,
September 25, 2019



Overview

Motivation

Review on interaction constraints:

1. Astrodynamics
2. Fluence regime
3. Momentum uncertainty
4. Thermo-mechanical „side-effects“
5. Destination orbit uncertainty
6. Hit rate
7. Beam broadening
8. Weather conditions
9. Laser safety

Conclusion and Outlook

Motivation: Space debris threats

Objects > 10 cm

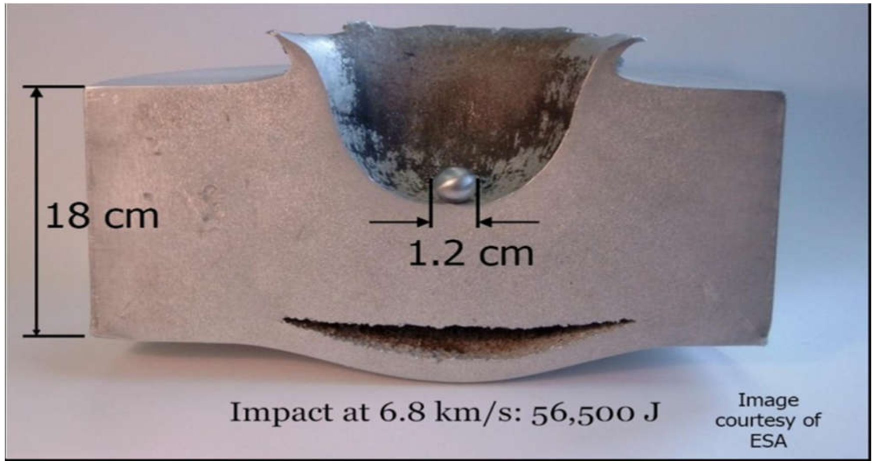
- Fragments, Rocket bodies, Defective satellites
- s/c destruction (→ Kessler syndrome)
- Monitoring & obstacle avoidance possible
- ≥ 5 cm: 15,000 catalogued ***and published*** TLE

Active satellites and debris objects > 10 cm in Earth orbit

Objects between 1 cm and 10 cm

main ROI for laser-based removal

- s/c wall penetration (→ loss of functionality)
- Difficult to detect
- 500,000 – 1,000,000 objects (estimated)

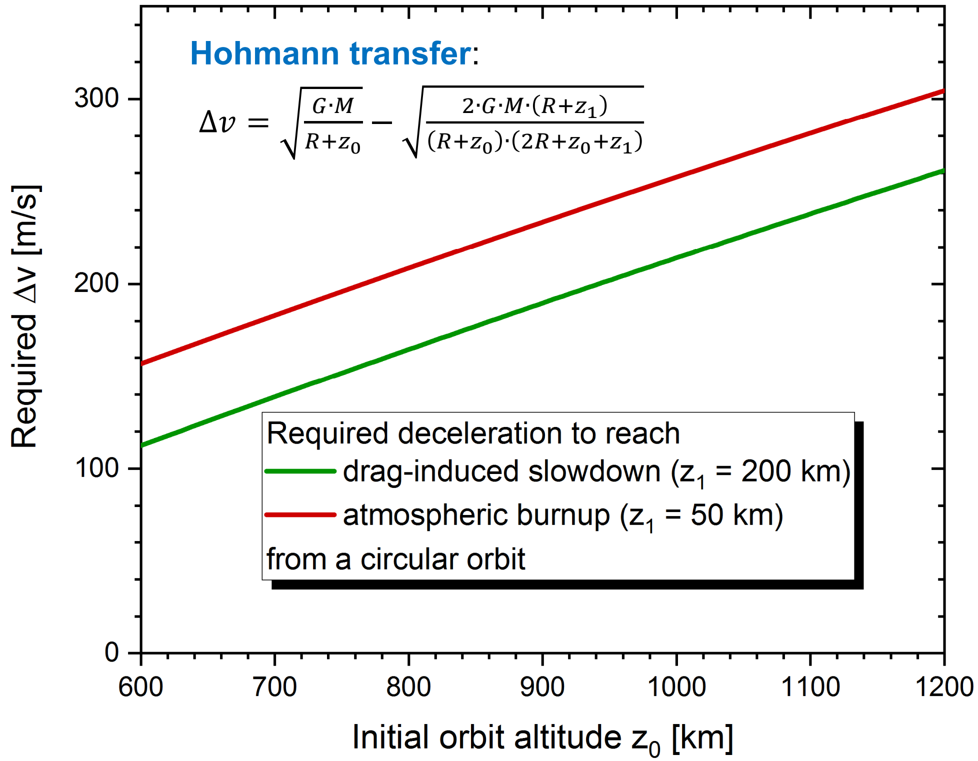


Impact of aluminum sphere in aluminum block @ 6.8 km/s

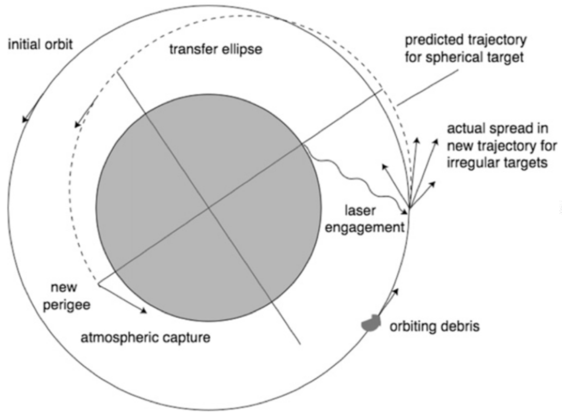
Requirements:
- Analysis of laser-target conjunction geometry and timespan

Constraint #1: Astrodynamics Constraints

Target deceleration for atmospheric burn-up



In-track / radial momentum transfer



$$H = \frac{v_v^2 + v_r^2}{2} - \frac{G \cdot M}{r}$$

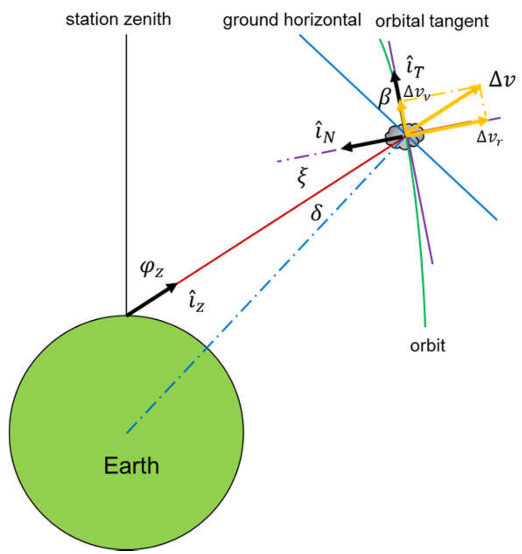
$$\Delta a = \frac{G \cdot M}{2H^2} \Delta H$$

$$\Delta r_p = (1-\varepsilon)\Delta a - a\Delta\varepsilon$$

$$\Delta r_a = (1+\varepsilon)\Delta a + a\Delta\varepsilon$$

C.R. Phipps et al., Removing orbital debris with lasers, Adv. Space Res. **49**: 1283 (2012)

Apogee lift + perigee lowering



adapted from: C.R. Phipps et al., Removing orbital debris with lasers, Adv. Space Res. **49**: 1283 (2012)

Requirements:
- High laser pulse energy
- Small laser spot size

Constraint #2: Laser fluence in ablative momentum coupling

Main requirement: Laser **fluence** *at the target surface*

$$\Delta v = \eta_c \cdot c_m \cdot \Phi \cdot A_{cs}/m$$

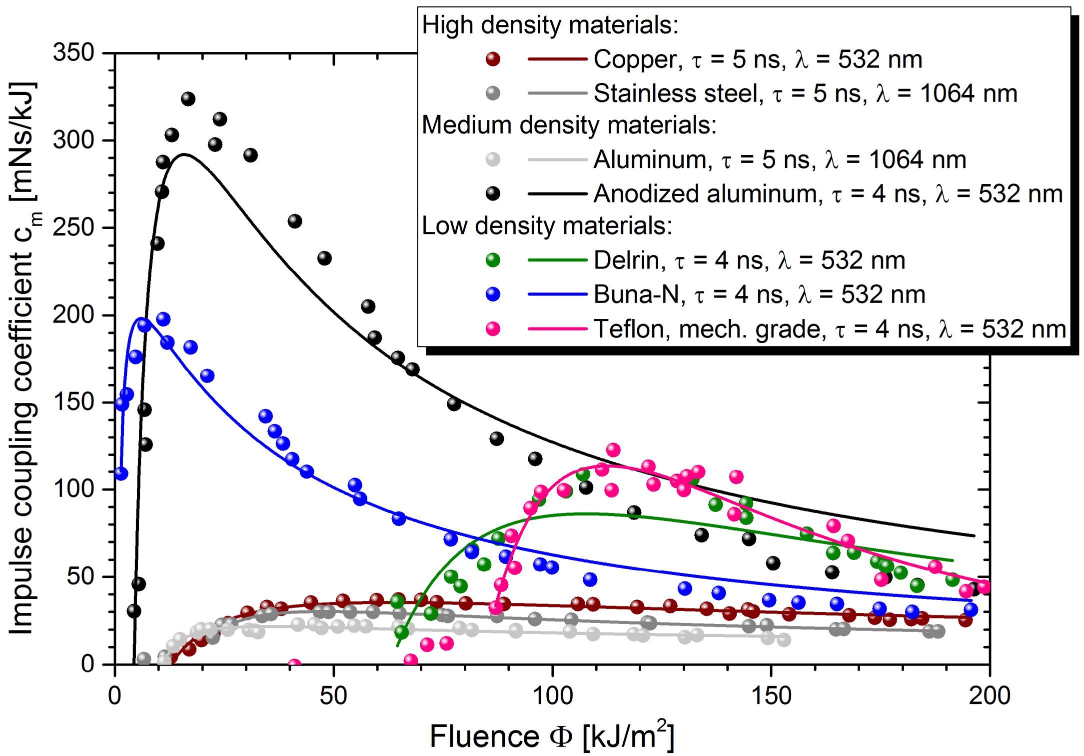
C. Phipps, Acta Astronaut. **93**: 418 (2014)

Key dependency: $c_m(\Phi) \approx \frac{\Phi-\Phi_0}{a+(\Phi-\Phi_0)} \cdot b \cdot 12.46 \cdot A^{7/16} \cdot \left(\frac{\sqrt{\tau}}{\lambda \cdot \Phi}\right)^c$

S. Scharring et al., Opt. Eng. **58**(1): 011004 (2018) following C. Phipps et al., J. Propul. Power **26**: 609 (2010)

Data for $\lambda = 1064\ nm$	Type	τ $[ns]$	Φ_0 $[J/cm^2]$	$c_{m,max}$ $[mNs/kJ]$	$\Phi_{opt}(c_{m,max})$ $[J/cm^2]$
Stainless steel	Exp.	5	1.7	30	4.8
Copper	Exp.	5	2.6	18	36
Aluminum	Exp.	5	2.2	24	8.4
Aluminum	Exp.	8	1.5	13	6.5
Aluminum	Mod.	1	1.1	24	3.5
Aluminum	Mod.	10	3.0	18	10.4

- Typical fluence ($\tau = 5 \ldots 10$ ns, λ = 1064 nm): $\approx 5 - 10\ J/cm^2$
- Threshold fluence: $\Phi_0 \propto \sqrt{\tau}$, dependencies: λ, τ, material



Experimental data from:
B.C. D'Souza, Development of Impulse Measurement Techniques for the Investigation of Transient Forces du Laser-Induced Ablation, PhD Thesis, University of Southern California (2007)

Requirements:
- Material reconnaissance
- Shape information
- Knowledge of orientation

Constraint #3. Momentum uncertainty

Laser-matter interaction code

EXPEDIT

EX*amination* **P***rogram for irr***E***gularly shape***D** *debr***I***s* **T***argets*

$$\vec{p} = \sum_j \vec{p_j} = \sum_j -c_m(\Phi_L, \vartheta) \cdot \Phi_L(\vec{r}) \cdot \cos\vartheta_j(\vec{r}) d\hat{n}_j(\vec{r})$$

S. Scharring et al., Opt. Eng. **58**(1): 011004 (2018)

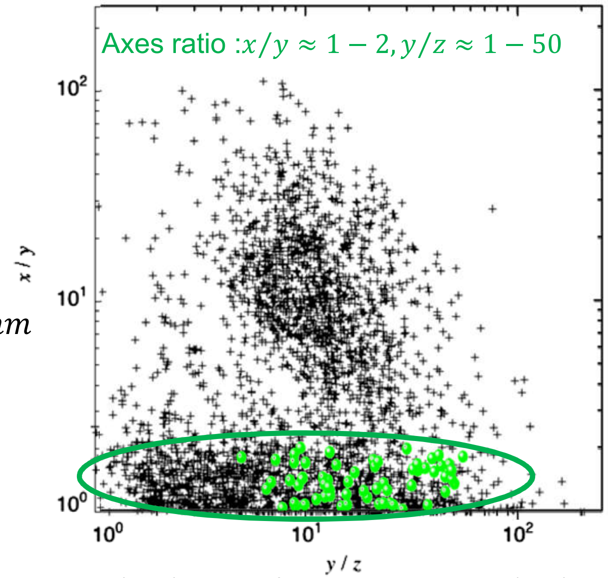
Laser: $\Phi = \Phi(\vec{r})$
Matter: *Finite surface elements (obj files)*
Interaction: $c_m(\Phi), \eta_{res}(\Phi)$

Simulation setup

- Laser specs: $E_L = 25\ kJ$, $\tau = 10\ ns$, $\lambda = 1064\ nm$
- Spot: $\emptyset = 0.67\ m$, $\langle\Phi\rangle = 7.2\ J/cm^2$
- Beam Discretization: 0.1 mm resolution
- Monte Carlo simulation:
  - Random target orientation
  - 2000 sample shots / target
  - Beam center = Target CMS

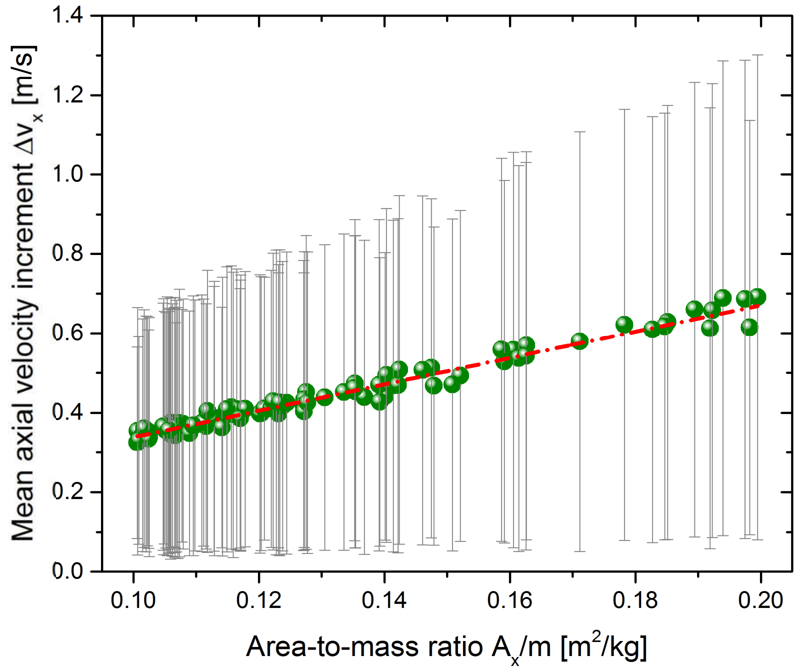
Targets

- 100, randomly generated
- Flake-like ellipsoids
- Material: aluminium
- Size: $L_c \in [0.01\ m; 0.1\ m]$



Targets (green) generated following crash test analysis (black) in: T. Hanada et al., Adv. Space Res. **44**(5): 558 – 567 (2009)

Velocity Increment Δv



→ Consideration of large momentum scatter necessary
→ Collision analysis for conceivable trajectories required

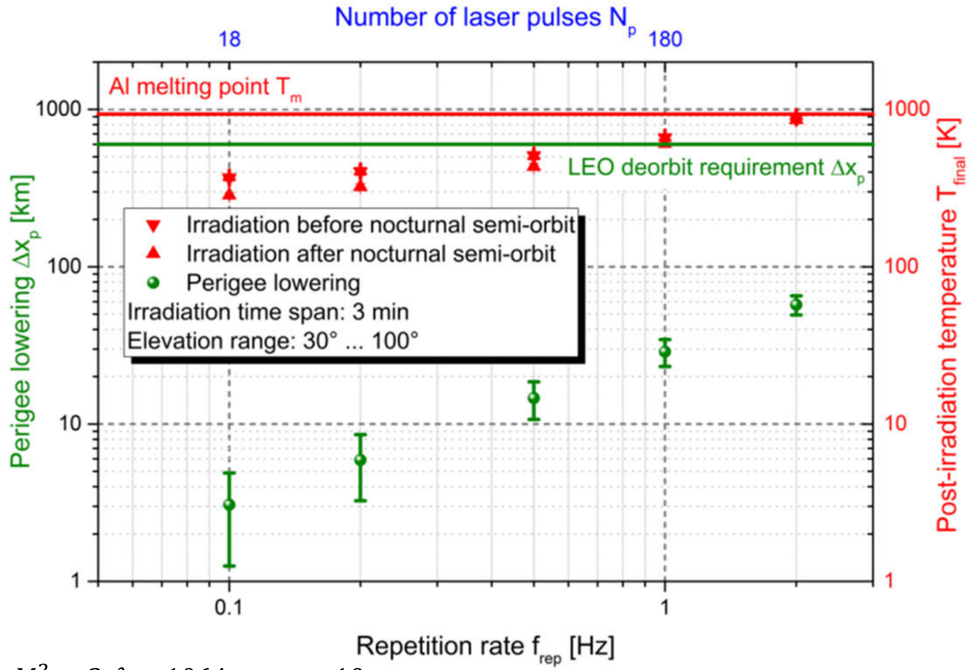
Requirements:
- Material reconnaissance
- Pulse number limitation
- Multi-pass irradiation
- Cooldown intervals

Constraint #4: Thermo-mechanical „side effects“

Structural integrity risks

- Residual heat in laser ablation:
  - target melting (flat, large → sphere, small)
- Fragmentation risks:
  - Low heat conductivity → thermal stress
  - Frequent, rapid heating cycles→ aging effects
  - Strong shock and rarefaction waves

Molten aluminum target after repetitive laser irradiation



S. Scharring et al., Removal of Small-Sized Space Debris by Laser-Ablative Momentum Generation, ILRS Workshop, Canberra, November 2018

Simulation setup

Laser specs: $E_L = 20\ kJ,\ M^2 = 2, \lambda = 1064\ nm, \tau = 10\ ns$
Transmitter: $D_{Telescope} = 8\ m,\ Str = 0.4$
Target: Al plate 2 x 2 x 0.1 cm, $\boldsymbol{\varepsilon = 0.09}$, $d_{spot} = 70\ cm$
Initial target temperature: $\boldsymbol{T_0 = 327.8\ (239.4)\ K}$ (dusk/dawn)
Circular orbit, 800 km altitude
Irradiation range: 30° - 100° elevation (3 minutes)
Monte Carlo study, up to 1000 samples each
Arbitrary target orientation, 0.42 µrad hit precision

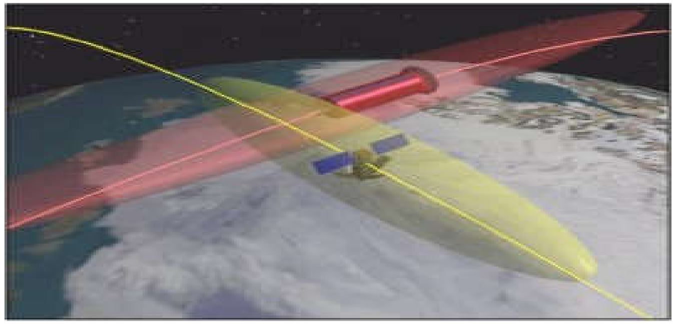
DLR

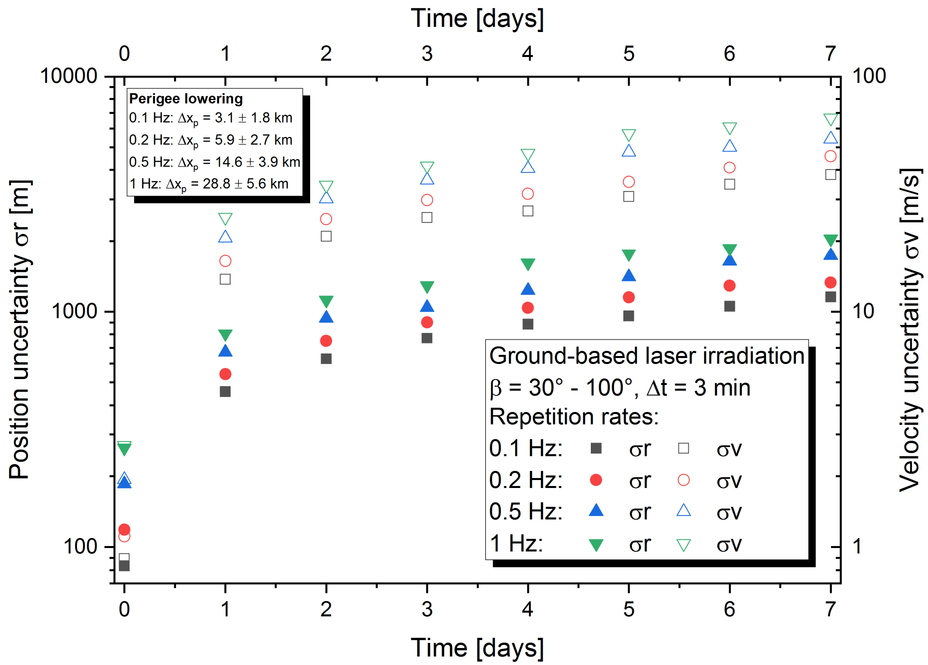
Requirements:
- Prior collision analysis
- Clearance for conceivable destination trajectories

Constraint #5. Predictive collision avoidance

Collateral damage prevention for active missions

Multi-pass irradiation
→ need for long-term safe debris maneuvering
→ information on impact of Δv on orbit uncertainty needed





Simulation setup

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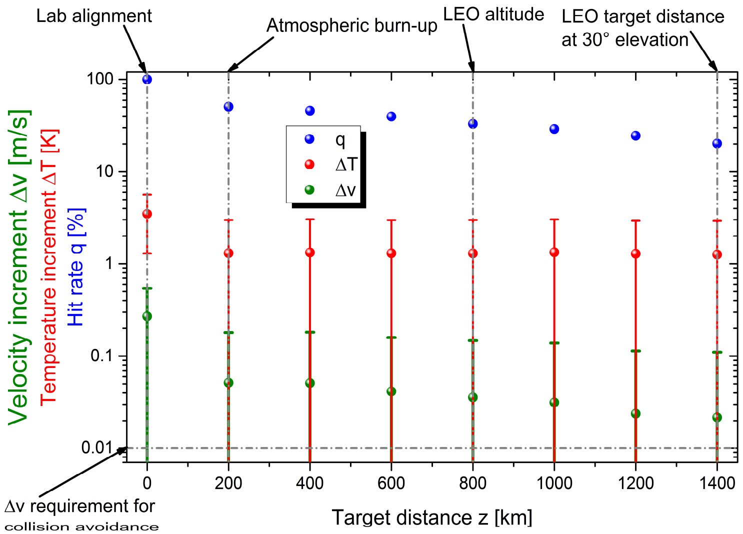
Transmitter: $D_{Telescope} = 8\ m,\ Str = 0.4$
Target: Al plate 2 x 2 x 0.1 cm, $d_{spot} = 70\ cm$
Circular orbit, 800 km altitude
Irradiation range: 30° - 100° elevation (3 minutes)
Monte Carlo study, up to 1000 samples each
Arbitrary target orientation, 0.42 μrad hit precision
Orbit propagation with ODEM software, $A/m = 0.1$

ODEM software used with friendly permission by DLR – Institute of Space Operations and Astronaut Training

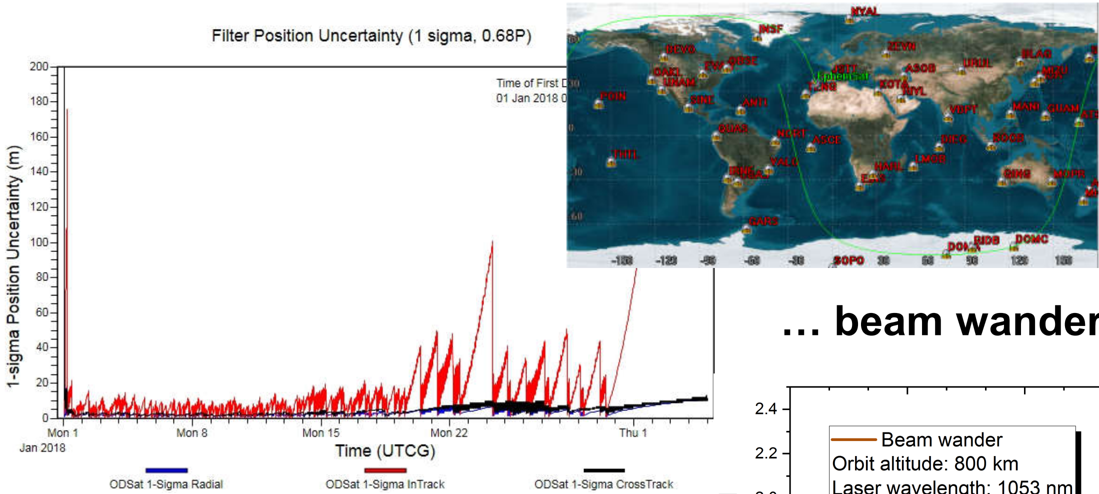
Requirements:
- target finetracking
- laser guide star
- tip/tilt correction

Constraint #6: Hit rate, affected by…



Simulations on thermo-mechanical coupling
Laser specs: $E_L = 20\ kJ,\ M^2 = 2, \lambda = 1064\ nm, \tau = 10\ ns$
Transmitter: $D_{Telescope} = 8\ m,\ Str = 0.4$
Target: Al plate 2 x 2 x 0.1 cm, $d_{spot} = 70\ cm$
Monte Carlo study, 10,000 samples each
Arbitrary target orientation, 0.42 µrad hit precision

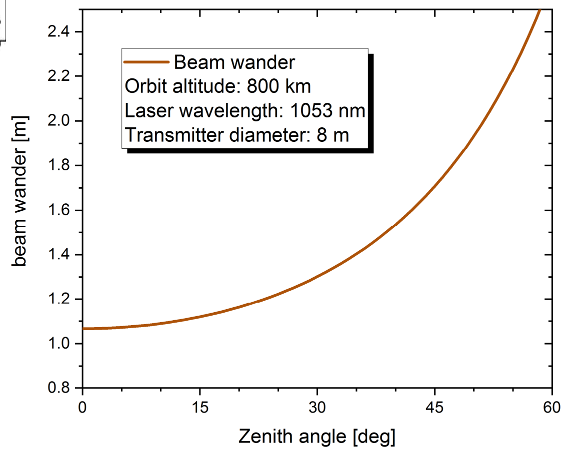
… debris tracking accuracy,



1-σ position uncertainty during laser ranging measurements to LEO (high inclination orbit) by a 46-station network; weather conditions: January, 11-year average

S. Scharring et al., Network performance analysis of laser-optical tracking for space situational awareness in the Lower Earth Orbit, AMOS paper (2019)

… beam wander,

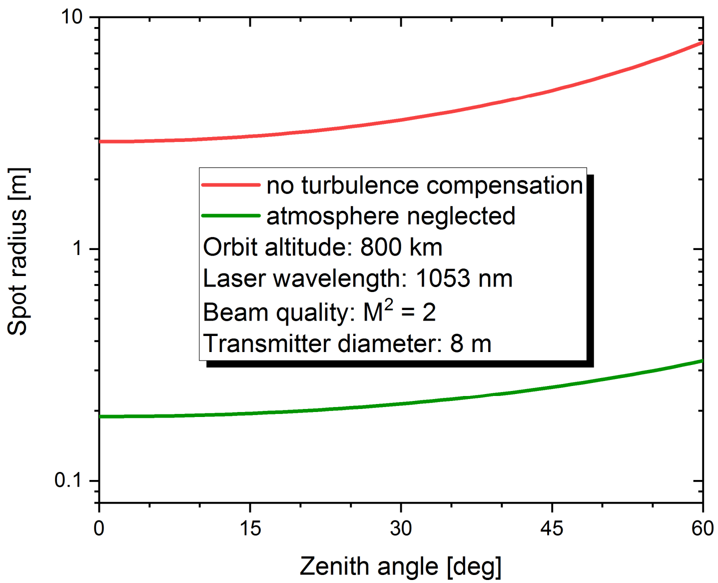


… and laser/transmitter pointing stability

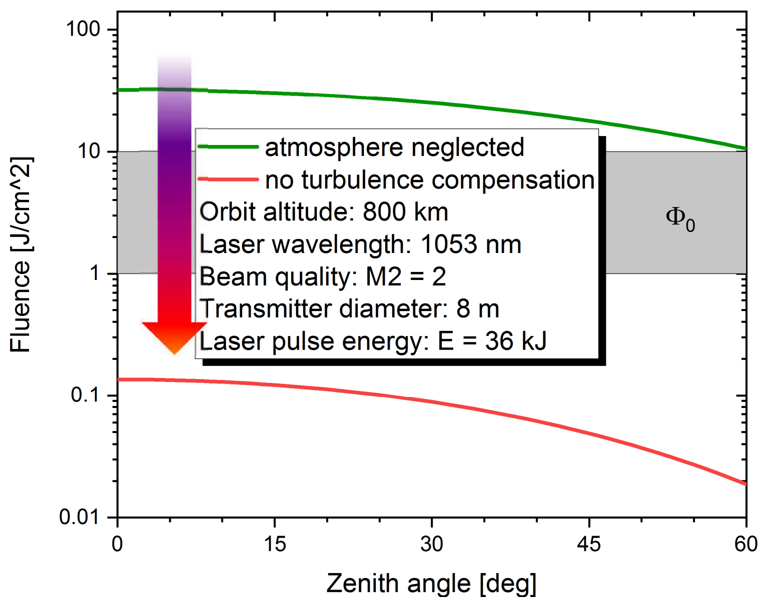
Requirement:
- adaptive optics

Constraint #7: Beam broadening

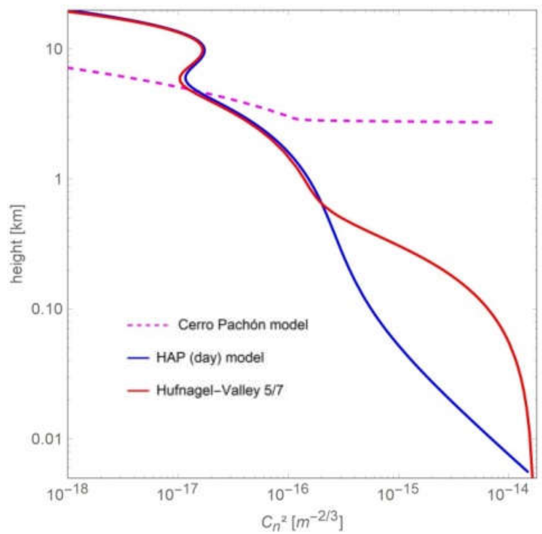
Spot size



Fluence



loss of function for uncompensated turbulence

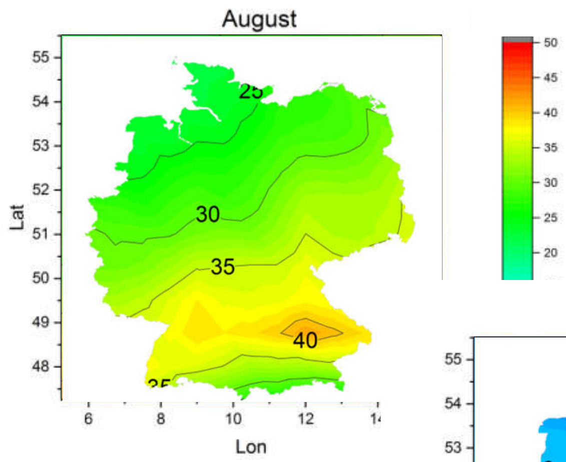


Laser pulse energy: 2 x 18 kJ, wavelength: 1053 nm (e.g., Laser Mégajoule beamlines)
M² = 2, transmitter diameter: 8m
Turbulence model: Hufnagel-Andrews-Phillipps (day)

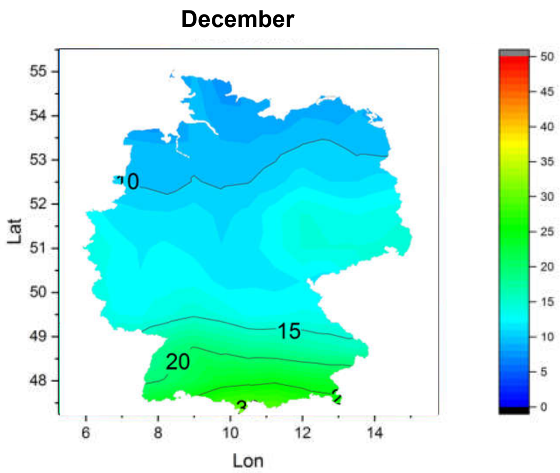
Requirements:
- site weather analysis
- network redundancies

Constraint #8: Weather conditions

Cloud cover: % Laser time fraction



Criterion:
cloud coverage < 25%

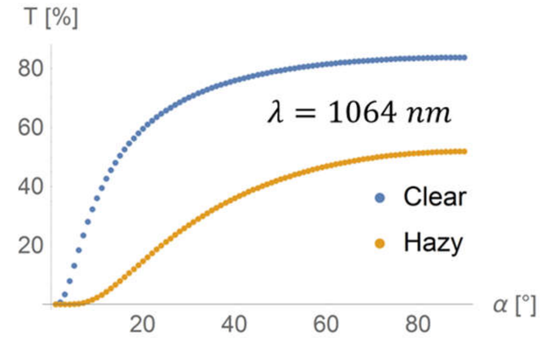


Based on 3-hourly data with 0.75° lat / lon resolution from 2007 through 2017 kindly provided from the European Center for Medium Weather Forecast

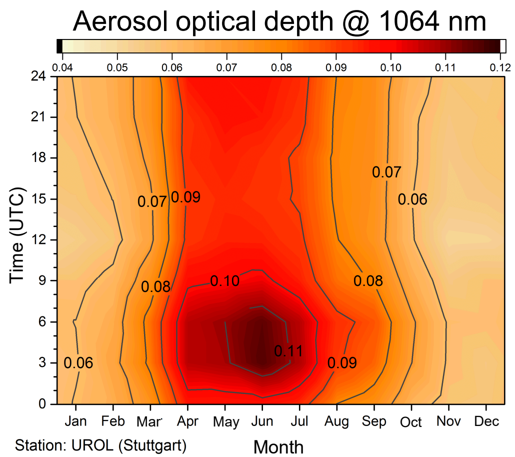
Extinction by aerosols and molecules

$$T(z) = \exp \int_0^z \frac{-\gamma(z)}{\sin\alpha} dz$$

T Transmission
γ Extinction
α Elevation angle



Database:
R. A. McClatchey et al, Optical Properties of the Atmosphere (3rd ed.), Environmental Research Papers **411**, Air Force Cambridge Research Laboratories (1972)



Station: UROL (Stuttgart)
9,2° **E**, 48,8° N

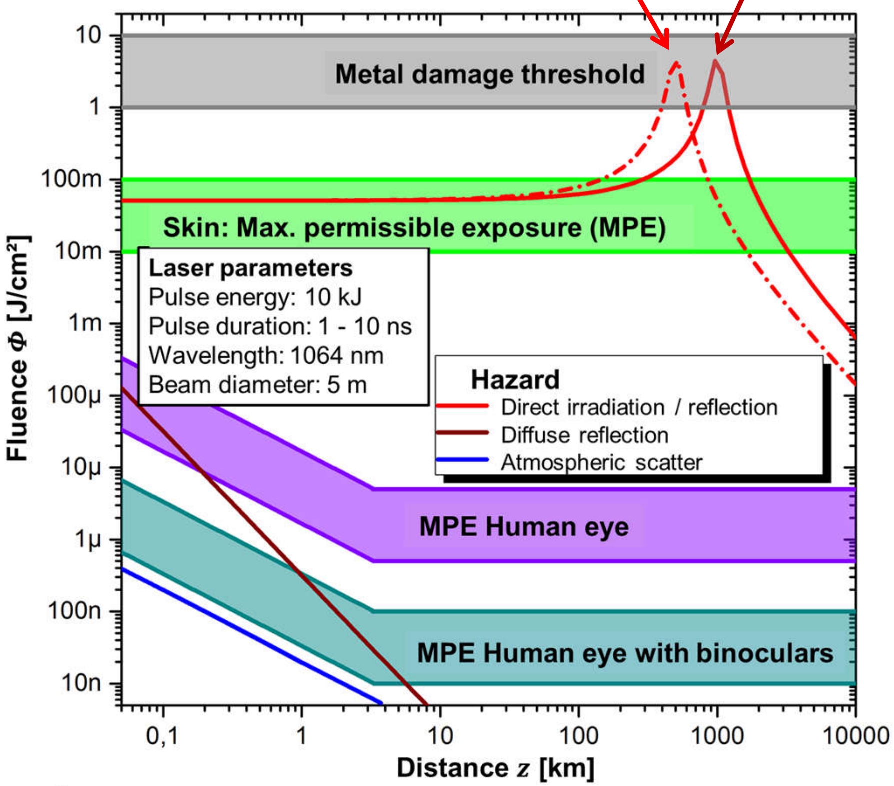
Based on 3-hourly data with 0.75° lat / lon resolution from 2007 through 2017 kindly provided from the European Center for Medium Weather Forecast

Requirements:
- predictive avoidance of unintentional irradiation

Constraint #9: Laser safety

Hazard analysis

Focus at 500 and 1000 km distance, resp.



Risk mitigation

Ground:
- Elevation geofencing
- Restricted HEL area

Air:
- Virtual radar (ADS-B, FLARM)
- Beam sector primary radar
- No-fly zone

Space:
- Orbital traffic monitoring
- Publication of irradiation times
- Laser protection (astronauts, sensors)

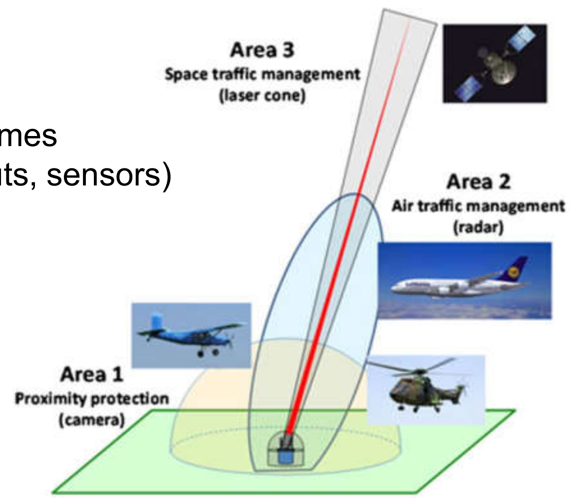


Fig. 15. Definition of the three safety areas.

B. Esmiller, Appl. Opt. **53**(31): I45 (2014)

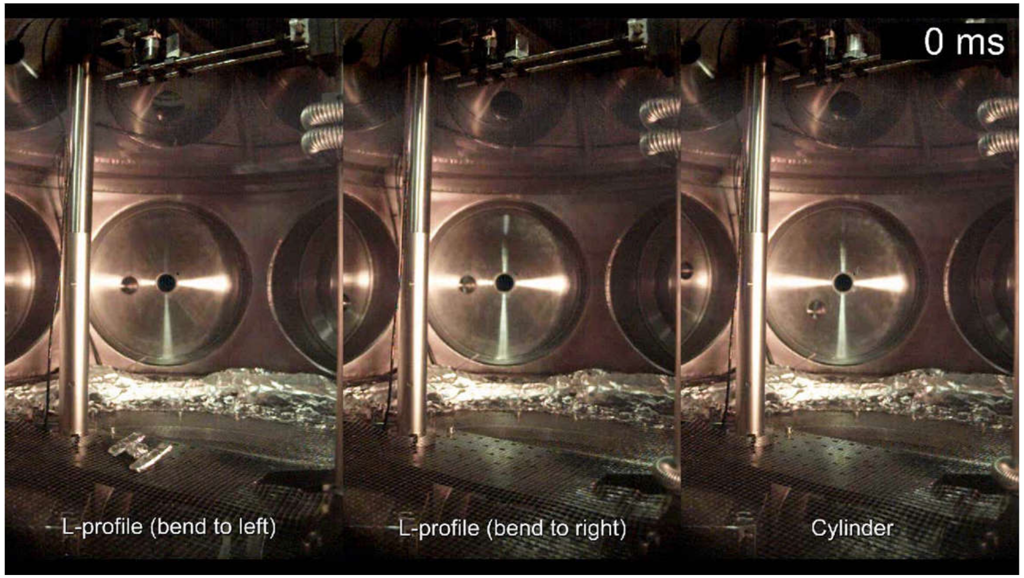
Summary: Interaction-related Requirements

1. Space Situational Awareness:
    1. Analysis of laser-target conjunction geometry and timespan
    2. Material reconnaissance, shape information, knowledge of orientation
    3. Prior collision analysis, trajectory corridor clearance
2. Laser and Transmitter:
    1. High laser pulse energy
    2. Laser guide star operation, tip/tilt correction
    3. Adaptive optics
3. Operation:
    1. Multi-pass irradiation
    2. Weather-related site analysis and station redundancy
    3. Predictive irradiation avoidance (ground/air/space)
4. **Nevertheless: Presently the sole solution for the management and removal of debris fragments**

a long way to go, but …

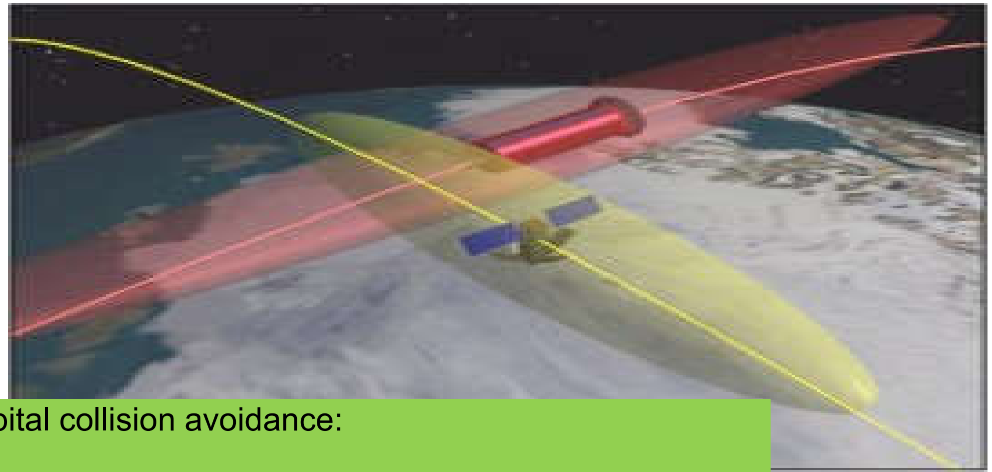
… small steps count: Collision avoidance

… with a single high energy laser pulse



Laser: $E = 80\,\mathrm{J}, \tau = 10\,ns, \lambda = 1064\,nm$
Spot fluence, size: $\emptyset = 3 \dots 4\,cm, \Phi_{max} \approx 10\,\,J/cm^2$
Target dimensions: $A_{cs} \approx 1 \dots 4\,cm^2, m \approx 1\,\,\dots 3\,g$
Velocity increment: $\Delta v_{exp} = 0.25\,\,\dots 2.8\,m/s$

R.-A. Lorbeer et al., Sci. Rep. 8: 8453 (2018)
https://www.nature.com/articles/s41598-018-26336-1



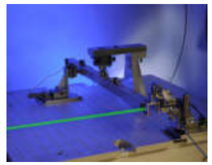
Orbital collision avoidance:

$\Delta v_{in-track} = -0.01\,\,m/s \rightarrow \Delta x_{in-track} = 2.5\,\,km/day$

*J. Mason et al., Adv. Space Res. 48: 1643 (2011)

… or even by photon pressure with COTS cw lasers

Current research @DLR-TP:
ESA study SSA P3-SST-XV – Laser Ranging Systems Evolution Study (LARAMOTIONS)



Thank you for your kind attention

Space Debris
Finnegan Scharring, 7 years
October 2017