Potential of using ground-based high-power lasers to decelerate the evolution of space debris in LEO

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Space Debris Mitigation Methods

Collision Avoidance

Rationale: UN COPUOS Guideline "Long-Term Sustainability of Outer Space Activities": → D.2: Techniques to prevent collision with and among debris

- Deceleration by $\Delta v = 1 \text{ mm/s}$  
  → in-track displacement by $\Delta x / \Delta t = 259.2 \text{ m/d}$
- D2D: accelerate target decelerate chaser

Removal by atmospheric burnup

Rationale: Outer Space Treaty:
- Art. I para. 2: Foster "free exploration and use"
- Art. VII: International liability of launching states
- Art. IX: Avoidance of "harmful contamination"

- In-track $\Delta v_t$ → Hohmann transfer → perigee lowering
- Radial $\Delta v_r$ → apogee lift

Required $\Delta v \approx 150 \ldots 250 \text{ m/s}$

Required deceleration to reach 
- drag-induced slowdown ($z_t = 200 \text{ km}$)
- atmospheric burnup ($z_t = 50 \text{ km}$)

from a circular orbit
Laser-matter Interaction: Photon Pressure

Laser-induced force to debris: \( \vec{F} = \left[ (A + R_D)\hat{k} - (R_D/2 + 2R_S \cos \theta)\hat{n} \right] \cdot 3.3 \, \text{nN/W} \cdot P_L \)

\[
\vec{F} = \left[ (A + R_D)\hat{k} - (R_D/2 + 2R_S \cos \theta)\hat{n} \right] \cdot 3.3 \, \text{nN/W} \cdot P_L
\]

Momentum coupling coefficient: \( c_m = F/P_L = \Delta p/E_L \)

Heat accumulation at debris: \( Q = \int A \cdot P_L \, dt \)

Coefficient of residual heat: \( \eta_{res} = \dot{Q}/P_L = Q/E_L \)

Laser backreflection from debris: \( P_{refl} = (R_S + R_D)P_L \)

Reflectivity:
\[
R = \frac{P_{refl}}{P_L} = \frac{E_{refl}}{E_L}
\]

Key parameter: Albedo \( R_A = R_S + R_D = 1 - A - T \)

Interaction dependencies: Material, temperature, wavelength \( \lambda \)

Scaling of \( \vec{F}, Q, P_{refl} \) with laser power: \( \text{(mostly) linear} \)
Laser-matter Interaction: Laser Ablation

Momentum coupling coefficient

\[ \text{Momentum: } c_m = 1 \ldots 1000 \mu N/W \]
(Photon pressure: \( c_m \approx 5 \) nN/W)

Ablation threshold \( \Phi_0 \propto \sqrt{\tau} \)

Example: Metals, ns-pulses: \( \Phi_0 = 1 \ldots 10 \) J/cm²

Key parameter: Fluence \( \Phi = E_L / A \)

Dependencies: Material, temperature, \( \lambda \), pulselength \( \tau \), fluence \( \Phi \)

Scaling of \( \vec{F} \), \( Q \), \( P_{refl} \) with laser power: non-linear
Laser Beam Propagation through the Atmosphere

**Compensation of MT Laser Beam Broadening**

\[ w_f(z) = \sqrt{\left(\frac{M^2 \lambda z}{\pi w_0}\right)^2 + 8 \left(\frac{\lambda z}{\pi r_0}\right)^2 \left(1 - 0.26 \left(\frac{r_0}{w_0}\right)^{1/3}\right)^2} \]

- **Tracking jitter**
  - adaptive optics, laser guidestar, tip/tilt compensation, \( \sigma = 0.1 \) arcsecs
- **Cloud cover (CF)**
  - no compensation
  - Statistical approach: feasibility up to 50% CF
- **Aerosol attenuation**
  - \( \sim 20\% \), no compensation
- **Molecular absorption**
  - transmission windows
- **Air breakdown**
  - pulselength \( \tau \gtrsim 100 \) ps

**Constraints**
Selection of Sample Targets

**LEO debris selection**
- USSTRATCOM TLE of July 2, 2019
- \( a \in [6950 \text{ km}; 7550 \text{ km}] \), \( \varepsilon \in [0.0; 0.2] \)
- \( i \in [65^\circ; 110^\circ] \)

**Data source:**
ESA DISCOS database
Fragment properties estimated using ESA MASTER-8 model
Target Deceleration – Photon Pressure

Laser configuration:
High power laser:
\[ P = 40 \, kW, \lambda = 1064 \, nm, M^2 = 1.5, cw \] (i.e., not pulsed)

Assumptions:
- Transmitter: 2.5 m Ø
- Adaptive optics + Laser guidestar
- Optical cross-sectional area
- Homogeneous beam profile
- Telescope outshining losses
- Atmospheric attenuation
- Photon pressure: debris albedo

Neglected:
- Tracking uncertainty
- Beam pointing jitter
- Shape, orientation

Direct station transit, irradiation for \( \mu \in [15^\circ; 65^\circ] \)
Target Deceleration – Photon Pressure

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Analytical estimate
\[ \Delta v = 40 \, kW \times dt \times 3.3 \, nN/W \times m \]

Irradiation for \( \zeta \in [15^\circ; 65^\circ] \)

Debris mass \( m \) [kg]

\( \Delta v \) [mm/s]

In-track displacement \( \Delta x/\Delta t \) [m/d]
Target Deceleration – Photon Pressure

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High power laser:
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- Tracking uncertainty
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- Shape, orientation
**Target Deceleration – Laser Ablation**

**Laser configurations:**
- **High power laser:**
  \[ \lambda = 1064 \text{ nm}, M^2 = 1.5, \text{cw} \]
- **High energy laser:**
  \[ \lambda = 1064 \text{ nm}, M^2 = 2.25, \tau = 5 \text{ ns} \]

**Assumptions:**
- Transmitter: 2.5 m Ø
- Adaptive optics + Laser guidestar
- Optical cross-sectional area
- Homogeneous beam profile
- Telescope outshining losses
- Atmospheric attenuation
- Photon pressure: debris albedo
- Ablation: Exp. \( c_m \) data (Al, Steel)

**Neglected:**
- Tracking uncertainty
- Beam pointing jitter
- Shape, orientation
Target Deceleration – Laser Ablation

Laser configurations:
- High power laser:
  \[ \lambda = 1064 \text{ nm}, M^2 = 1.5, \text{cw} \]
- High energy laser:
  \[ f = 1 \text{ Hz}, \lambda = 1064 \text{ nm}, M^2 = 2.25, \tau = 5 \text{ ns} \]

Assumptions:
- Transmitter: 2.5 m Ø
- Adaptive optics + Laser guidestar
- Optical cross-sectional area
- Homogeneous beam profile
- Telescope outshining losses
- Atmospheric attenuation
- Photon pressure: debris albedo
- Ablation: Exp. \( c_m \) data (Al, Steel)

Neglected:
- Tracking uncertainty
- Beam pointing jitter
- Shape, orientation
Target Heating

Laser configurations:
- High power laser: \( \lambda = 1064 \text{ nm}, M^2 = 1.5, \text{cw} \)
- High energy laser: \( f = 1 \text{ Hz}, \lambda = 1064 \text{ nm}, M^2 = 2.25, \tau = 5 \text{ ns} \)

Risks:
- Target meltdown
- Fragmentation
- Detonation of partially passivated objects
Global Framework for Operational Safety

Avoid intentional destruction (UN Space Debris Mitigation Guideline #4)

Avoid harmful activities (UN Space Debris Mitigation Guideline #4)

Limit the probability of accidental collision in orbit (UN Space Debris Mitigation Guideline #3)

Perform an assessment of the risk of break-up of space objects due to such illumination; and, as necessary, observe appropriate measures of precaution (UN Guidelines for the Long-term Sustainability of Outer Space, B.10)

Analyze the probability of accidental illumination of passing space objects by laser beams (UN Guidelines for the Long-term Sustainability of Outer Space, B.10)

Outdoor laser beam propagation is admissible if other technical or organizational measures can be provided for which ensure that the exposition to laser radiation stays below the MPE. (DGUV 11, §7.3)

Dual use goods with certain specifications as of EU 2015/2420: Detectors, cameras, LIDAR equipment, optical tracking equipment, optical components, high power lasers

Limit the probability of accidental collision in orbit (UN Space Debris Mitigation Guideline #3)

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## Summary: Rationales and Risks of Laser-based Debris Mitigation (LDM)

### Benefits
- Debris vs. debris collision avoidance
- Access to many small debris objects
- Operation from ground
- Photon pressure: COTS technology
- Laser ablation: suitable even for debris removal

### Risks
- Laser dazzling
- Debris meltdown / fragmentation
- Stored energy detonation
- Weaponization

### Challenges
- High power laser technology
- Turbulence compensation
- High-precision tracking
- Debris reconnaissance

### Outlook (reverse roadmap)

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Thank you for your kind attention

Acknowledgements for …

… DLR Institutional funding
… European Space Agency (ESA)

via ESA Contract No. 4000127148/19/D/CT