Interaction constraints for laser-based removal of space debris

Stefan Scharring, Raoul-Amadeus Lorbeer, Jürgen Kästel, Kevin Bergmann, Wolfgang Riede

Institute of Technical Physics, Stuttgart
German Aerospace Center

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

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
Constraint #1: Astrodynamics Constraints

**Target deceleration for atmospheric burn-up**

**Hohmann transfer:**

\[ \Delta v = \left( \frac{GM}{R+z_0} - \frac{2GM(R+z_1)}{(R+z_0)(2R+z_0+z_1)} \right) \]

- Required deceleration to reach drag-induced slowdown \((z_1 = 200 \text{ km})\)
- Atmospheric burnup \((z_1 = 50 \text{ km})\)
- From a circular orbit

**In-track / radial momentum transfer**

\[ H = \frac{\nu_0^2 + \nu_T^2}{2} - \frac{GM}{r} \]
\[ \Delta a = \frac{GM}{2H^2} \Delta H \]
\[ \Delta r_p = (1 - \varepsilon)\Delta a - a\Delta \varepsilon \]
\[ \Delta r_a = (1 + \varepsilon)\Delta a + a\Delta \varepsilon \]

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

---

Constraint #2: Laser fluence in ablative momentum coupling

Main requirement: Laser fluence at the target surface
\[ \Delta v = \eta_c \cdot c_m \cdot \Phi \cdot A_{cs}/m \]


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


<table>
<thead>
<tr>
<th>Data for ( \lambda = 1064 ) nm</th>
<th>Type</th>
<th>( \tau ) [ns]</th>
<th>( \Phi_0 ) [J/cm(^2)]</th>
<th>( c_{m,\text{max}} ) [mNs/kJ]</th>
<th>( \Phi_{\text{opt}}(c_{m,\text{max}}) ) [J/cm(^2)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>Exp.</td>
<td>5</td>
<td>1.7</td>
<td>30</td>
<td>4.8</td>
</tr>
<tr>
<td>Copper</td>
<td>Exp.</td>
<td>5</td>
<td>2.6</td>
<td>18</td>
<td>36</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Exp.</td>
<td>5</td>
<td>2.2</td>
<td>24</td>
<td>8.4</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Exp.</td>
<td>8</td>
<td>1.5</td>
<td>13</td>
<td>6.5</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Mod.</td>
<td>1</td>
<td>1.1</td>
<td>24</td>
<td>3.5</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Mod.</td>
<td>10</td>
<td>3.0</td>
<td>18</td>
<td>10.4</td>
</tr>
</tbody>
</table>

- Typical fluence (\( \tau = 5 \ldots 10 \) ns, \( \lambda = 1064 \) nm): \( \approx 5 \ldots 10 \) J/cm\(^2\)
- Threshold fluence: \( \Phi_0 \propto \sqrt{\tau} \), dependencies: \( \lambda, \tau, \) material
Constraint #3. Momentum uncertainty

Laser-matter interaction code

**EXPEDIT**

**Examination Program for Irregularly shaped debris Targets**

\[ \mathbf{\dot{p}} = \sum_j \mathbf{\dot{p}}_j = \sum_j -c_m(\Phi_L, \theta) \cdot \Phi_L(\mathbf{r}) \cdot \cos \theta_j(\mathbf{r}) \, d\mathbf{\Phi}_j(\mathbf{r}) \]


**Laser:** \( \Phi = \Phi(\mathbf{r}) \)

**Matter:** Finite surface elements (obj files)

**Interaction:** \( c_m(\Phi), \eta_{res}(\Phi) \)

Targets

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

Axes ratio \( x/y \approx 1 - 2, y/z \approx 1 - 50 \)

Velocity Increment \( \Delta \nu \)

Simulation setup

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

\[ \begin{align*}
\mathbf{\dot{p}}_j &= -c_m(\Phi_L, \theta) \cdot \Phi_L(\mathbf{r}) \cdot \cos \theta_j(\mathbf{r}) \, d\mathbf{\Phi}_j(\mathbf{r}) \\
\end{align*} \]

\( \langle \Phi \rangle = 7.2 \, J/cm^2 \)

\[ \begin{align*}
\Delta \nu &\approx \frac{E_L}{M} \\
\end{align*} \]

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

Simulation setup

Laser specs: \( E_L = 20 \, kJ \), \( M^2 = 2, \lambda = 1064 \, nm, \tau = 10 \, ns \)
Transmitter: \( D_{Telescope} = 8 \, m, \, St \tau = 0.4 \)
Target: Al plate 2 x 2 x 0.1 cm, \( \varepsilon = 0.09, \, d_{spot} = 70 \, cm \)

Initial target temperature: \( T_0 = 327.8 \, (239.4) \, K \) (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

Requirements:
- Material reconnaissance
- Pulse number limitation
- Multi-pass irradiation
- Cooldown intervals
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 \( \Delta v \) on orbit uncertainty needed

Simulation setup

Laser specs: \( E_L = 20 \, kJ \), \( M^2 = 2, \lambda = 1064 \, nm, \tau = 10 \, ns \)
Transmitter: \( D_{Telescope} = 8 \, m, St = 0.4 \)
Target: Al plate \( 2 \times 2 \times 0.1 \, \text{cm} \), \( d_{spot} = 70 \, cm \)
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, \( A/m = 0.1 \)
Constraint #6: Hit rate, affected by...

- debris tracking accuracy,
- beam wander,

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

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

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

Constraint #7: Beam broadening

**Spot size**

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)

**Fluence**

Laser pulse energy: E = 36 kJ
Orbit altitude: 800 km
Laser wavelength: 1053 nm
Beam quality: M² = 2
Transmitter diameter: 8 m

Requirement:
- adaptive optics

*loss of function for uncompensated turbulence*
Constraint #8: Weather conditions

Cloud cover: % Laser time fraction

Extinction by aerosols and molecules

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

- \( T \) Transmission
- \( \gamma \) Extinction
- \( \alpha \) Elevation angle


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
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)

Requirements:
- Predictive avoidance of unintentional irradiation
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
... small steps count: Collision avoidance

... with a single high energy laser pulse

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

Orbital collision avoidance:
\[ \Delta v_{\text{in-track}} = -0.01 \text{ m/s} \rightarrow \Delta x_{\text{in-track}} = 2.5 \text{ km/day} \]

... 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