Debris-debris collision avoidance using medium power ground-based lasers

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1) Introduction: approaches to mitigate the Kessler collision cascade

2) Existing laser debris removal proposals

3) A new laser debris-debris collision avoidance scheme

4) Summary
1) Introduction: approaches to mitigate the Kessler collision cascade

2) Existing laser debris removal proposals

3) A new laser debris-debris collision avoidance scheme

4) Summary
The Kessler Collision Cascade might be a reality*


source: Kessler & Cour-Palais, JGR 83(A6) 1978
Three options to solve the Kessler problem

1. debris mitigation plans (e.g. IADC guidelines)
2. debris removal
3. collision avoidance (active and/or non-active payloads)
Models indicate that debris mitigation alone will not be enough to prevent a cascading effect.

LEO Environment Projection for *No Future Launch Scenario*

1) Introduction: approaches to mitigate the Kessler collision cascade

2) Existing laser debris removal proposals

3) A new laser debris-debris collision avoidance scheme

4) Summary
Existing laser debris removal proposals are based on ablation induced recoil

adapted from: Phipps et al., J. Propulsion, 26:4(2010)
Ablation requires high threshold laser intensities

\[ T_{\text{max}} = \sqrt[4]{\frac{AI_{\text{max}}}{\varepsilon_{\text{hg}}\sigma}} \]

A: debris absorption
I: laser intensity
\(\varepsilon\): debris emissivity
\(\sigma\): Stefan-Boltzmann constant

Example: boiling point of Aluminium: 2792 K, if \(\varepsilon=A\)
\[ \rightarrow \text{minimum intensity } I=3.4 \text{ MW/m}^2 \]
Ablation requires high *threshold* laser intensities

\[
T_{\text{max}} = \sqrt[4]{\frac{AI_{\text{max}}}{\varepsilon_{\text{hg}}\sigma}}
\]

A: debris absorption  
I: laser intensity  
\(\varepsilon\): debris emissivity  
\(\sigma\): Stefan-Boltzmann constant

Example: boiling point of Aluminium: 2792 K, if \(\varepsilon=1\)  
→ *minimum* intensity \(I=3.4\) MW/m²  
→ high laser power and/or large telescopes
Laser Debris-debris collision avoidance

Proposed systems require lasers which are not commercially available today.

<table>
<thead>
<tr>
<th>proposed by</th>
<th>based</th>
<th>Telescope diameter</th>
<th>average optical power</th>
<th>Pulse length</th>
<th>Pulse energy</th>
<th>Fluence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monroe 1993</td>
<td>ground</td>
<td>10m</td>
<td>5000kW</td>
<td>N/A continuous</td>
<td>N/A continuous</td>
<td>N/A continuous</td>
</tr>
<tr>
<td>Campell 1996</td>
<td>Project Orion</td>
<td>ground</td>
<td>3.5m</td>
<td>25kW</td>
<td>5ns</td>
<td>5kJ</td>
</tr>
<tr>
<td>Schall 2002</td>
<td>space</td>
<td>2.5m</td>
<td>100kW</td>
<td>100ns</td>
<td>1kJ</td>
<td>10 J/cm²</td>
</tr>
</tbody>
</table>
Monroe’s proposed continuous laser system could be used as a laser ASAT weapon

Time in [s] to heat up a 1mm Al plate to 673 K using a 10m / 5 MW system

Assumptions: Turbulence according to Hufnagel/Valley 5/7, AO: adaptive optics correction according to ABL ref.
High fluence pulses are potentially dangerous for solar cells, radiators and optics

Estimated threshold for catastrophic laser damage

<table>
<thead>
<tr>
<th>Components</th>
<th>Impulse and Stress (J cm(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensors</td>
<td></td>
</tr>
<tr>
<td>Glass optics</td>
<td>8 (^4) (out of band)</td>
</tr>
<tr>
<td>Detectors:(^5)</td>
<td></td>
</tr>
<tr>
<td>Si:X</td>
<td>100</td>
</tr>
<tr>
<td>InSb or HgCdTe</td>
<td>2</td>
</tr>
<tr>
<td>Power</td>
<td></td>
</tr>
<tr>
<td>Solar cells: 30 (\mu m) silicon</td>
<td>8</td>
</tr>
<tr>
<td>and a 20 (\mu m) glass overcoat</td>
<td></td>
</tr>
<tr>
<td>Thermal Control</td>
<td></td>
</tr>
<tr>
<td>Thermal wrap:(^7), 10 layers of 0.25 mil aluminized mylar with 2 mil kapton overlayer</td>
<td>-</td>
</tr>
<tr>
<td>Radiator: silver on glass</td>
<td>8</td>
</tr>
<tr>
<td>8 mil thickness(^7), (A=0.07, \epsilon=0.8)</td>
<td></td>
</tr>
<tr>
<td>Structural</td>
<td></td>
</tr>
<tr>
<td>Anodized aluminium plate:</td>
<td></td>
</tr>
<tr>
<td>1 mm thick(^6), (A=0.16, \epsilon=0.76) with back-surface flat paint, (\epsilon=0.22)</td>
<td>(1.6 \times 10^3)</td>
</tr>
</tbody>
</table>

source: Federation of American Scientists, Laser ASAT Test Verification, 1991
1) Introduction: approaches to mitigate the Kessler collision cascade

2) Feasibility of laser debris sweepers

3) A new laser debris-debris collision avoidance scheme

4) Summary
Clearing the entire orbits is not necessary in order to avoid the Kessler cascade.

**LEO Environment Projection for Postmission Disposal (PMD) and Active Debris Removal (ADR) Scenarios**

- **PMD**
- **PMD + ADR02**
- **PMD + ADR05**

Collision avoidance requires high accuracy all-on-all conjunction analysis

High accuracy:
- avoids false alarms
- enables small avoidance maneuvers
Given high accuracy predictions, medium power lasers might be used to prevent the Kessler syndrome.

<table>
<thead>
<tr>
<th>Product</th>
<th>Prediction (days)</th>
<th>Accuracy (m)</th>
<th>Accuracy (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Ranging (ILRN &quot;truth&quot;)</td>
<td>0</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Fence (raw direction cosines)</td>
<td>0</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>High Accuracy Catalog + SP</td>
<td>10</td>
<td>500</td>
<td>50</td>
</tr>
<tr>
<td>Public Catalog + SGP4</td>
<td>10</td>
<td>5000-25000</td>
<td>1000</td>
</tr>
<tr>
<td>Public Catalog + new scheme</td>
<td>10</td>
<td>500-2000</td>
<td>50-200</td>
</tr>
</tbody>
</table>

→ Compared to debris removal (~100m/s), for debris collision avoidance a small push is sufficient (~0.01m/s)
Our approach focuses on radiation pressure, not on ablation.

\[
\vec{F} = \frac{h \nu dN}{c \, dt} = \frac{IA}{c}
\]

- \(A\): illuminated debris area
- \(I\): laser intensity
- \(h\): Planck constant
- \(c\): speed of light
- \(dN/dt\): photon stream

→ no threshold intensity necessary, but area-to-mass ratio crucial.
A first case study assumes use of available equipment to mitigate debris collisions in sun synchronous orbits.

Case study: laser system

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<tr>
<th>Location</th>
<th>Antarctica (4 km altitude)</th>
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<tbody>
<tr>
<td>Power</td>
<td>10 kW continuous</td>
</tr>
<tr>
<td>Telescope</td>
<td>1.5 m diameter</td>
</tr>
<tr>
<td>Adaptive optics</td>
<td>ABL performance + guide star</td>
</tr>
</tbody>
</table>

source: IPG photonics

source: L3 communications
Resulting intensities depend on satellite orbit and the location of the laser system.

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<th>Orbit</th>
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<td>Apogee</td>
<td>875 km</td>
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<tr>
<td>Inclination</td>
<td>98.4</td>
</tr>
<tr>
<td>Area</td>
<td>1 m²</td>
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Case study shows promising range displacements

Range displacement illuminating for 1st half of each pass.

→ displacement sufficient in the context of accuracy

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Multiple illuminations increase range displacement

![Graph showing range displacement over time with multiple passes.](image-url)
Useful displacements are possible for a range of area-to-mass ratios.
A area-to-mass ratio of 0.1 or larger includes a large part of recently released debris.

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### Summary

#### Status:
- Laser ablation debris removal is possible in theory, but still a challenging and costly endeavor, as necessary lasers are not commercially available.
- High accuracy conjunction analysis is necessary for collision avoidance, but standard TLE data might be sufficient with modern propagator and fitting.
- First case study suggests that laser debris-debris collision avoidance possible with commercially available hardware.

#### To do:
- Look into all aspects of a collision avoidance system, determine optimal setup and location.
- Determine effective strategies of use to avoid the Kessler syndrome.
- Laser safety via international laser clearinghouse process?
Laser propagation:

High accuracy conjunction analysis using public TLEs:

Cascading Debris:


Additional Information

Laser propagation:

High accuracy conjunction analysis using public TLEs:

Cascading Debris:


BACKUP
Fitting a series of TLEs coupled with a modern propagator, higher accuracy predictions are possible.
Compared to public TLEs + SGP4, new fitting scheme predictions are significantly more accurate.
Given high accuracy predictions, medium power lasers might be use to prevent the Kessler syndrome.


→ Compared to debris removal (~100m/s), for debris collision avoidance a small push is sufficient (~0.01m/s)

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