Exploring the Use of a Ground-Based Laser System to Deorbit Small Orbital Debris

Thomas J. Colvin, Jericho Locke

NASA's Office of Technology, Policy, and Strategy (OTPS)

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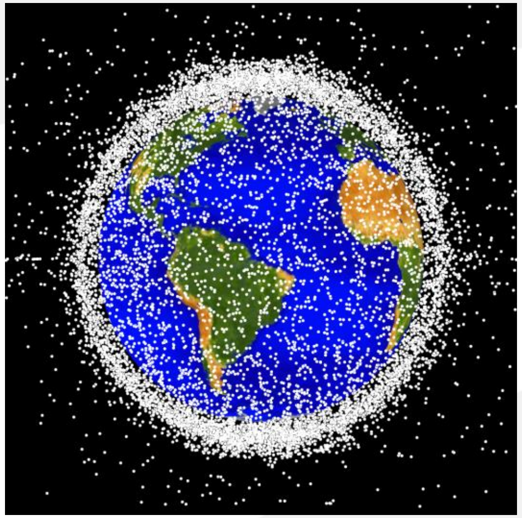
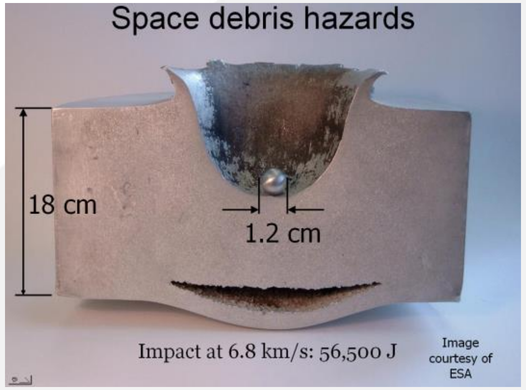
Risks From Orbital Debris are Growing

- Orbital debris: any human-made object orbiting Earth that no longer serves any useful purpose

- Risk—probability times consequence—grows with the number of debris and spacecraft
  - About 20,000 pieces of debris that we can track and avoid
  - Up to 100 million pieces of debris that we do not track and risk a mission-ending collision with active spacecraft





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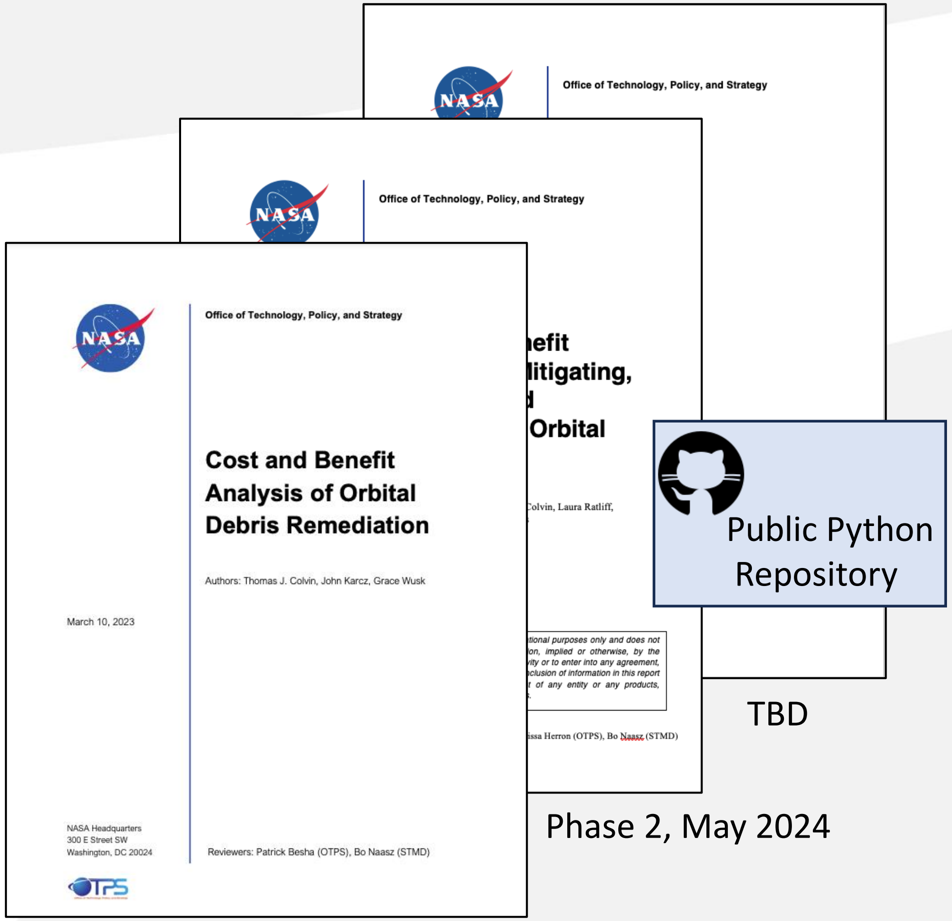
Ongoing Work Related to Debris

- OTPS is building a capability to:
  - Calculate net present value for actions to mitigate, track, and remediate debris
  - Identify optimal portfolios of actions to reduce risk
- Phase 1 study in 2023
  - Estimated costs and benefits of debris remediation
  - Found the two most cost-effective methods could be performed with ground- or space-based laser systems
- Phase 2 study in 2024:
  - Improved risk calculations by modeling new sources of debris, including mm-size debris, and orbital decay
  - Broadening scope beyond remediation to include mitigation and tracking of debris
  - Found that laser debris remediation may be among the most valuable of all actions considered



Phase 1, March 2023

Phase 2, May 2024

TBD

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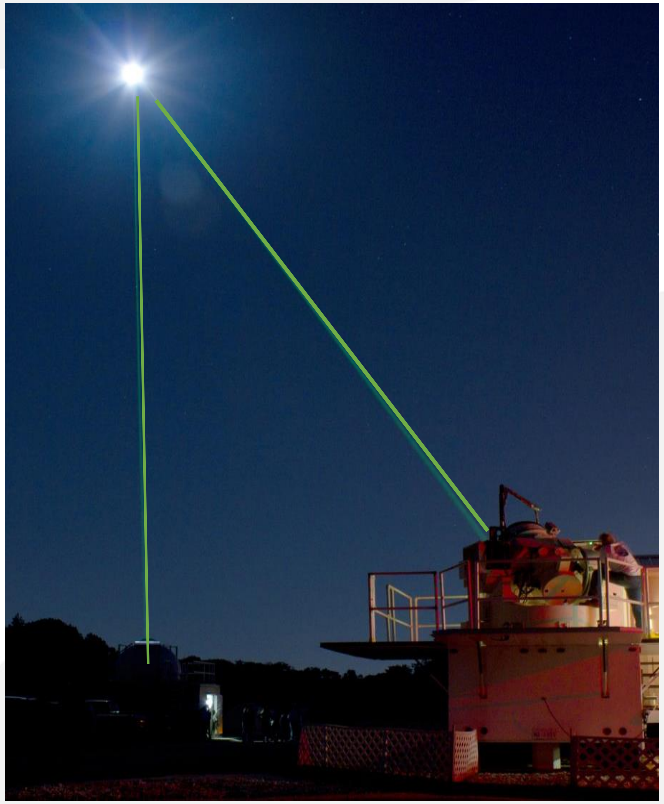
Feasibility of Remediation with Lasers?

- OTPS is doing follow-on work to analyze technical and policy feasibility
- Designed and analyzed a reference concept that may be achievable and protects a core NASA mission
- Organized a technical interchange meeting (TIM) to characterize the major *technical* gaps associated with a reference concept



Goddard's Laser Ranging Facility directs a laser toward the Lunar Reconnaissance Orbiter: NASA

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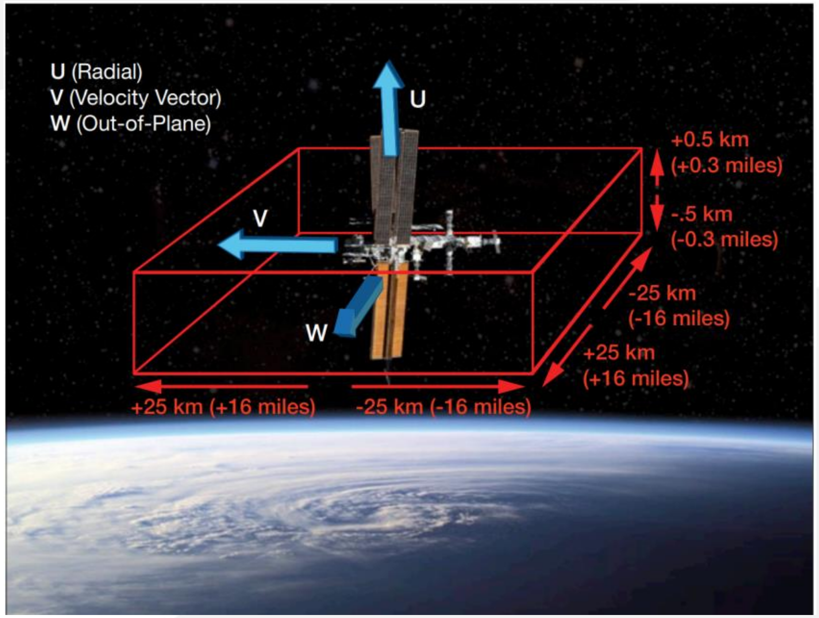
Reference Concept

- **Goal**: Protect crewed platforms in LEO from potentially lethal strikes of currently untracked orbital debris.
- **Context**:
  - U.S. modules on ISS shielded to 8 mm and can avoid > 10 cm debris.
  - Unmitigated risk remains for 1 – 10 cm debris, which may be ~20 times more likely to strike the ISS than tracked debris.
- **How**:
  - Ground-based laser nudges 1-10 cm debris (by ablation) to reduce the amount of time debris would otherwise spend crossing the path of ISS.
- **Performance Metric:**
  - Cumulative amount of time debris spends inside safety zone (400 km +/- 5 km)



The imaginary 'pizza box' around the ISS, used for conjunction assessments. Credit: NASA

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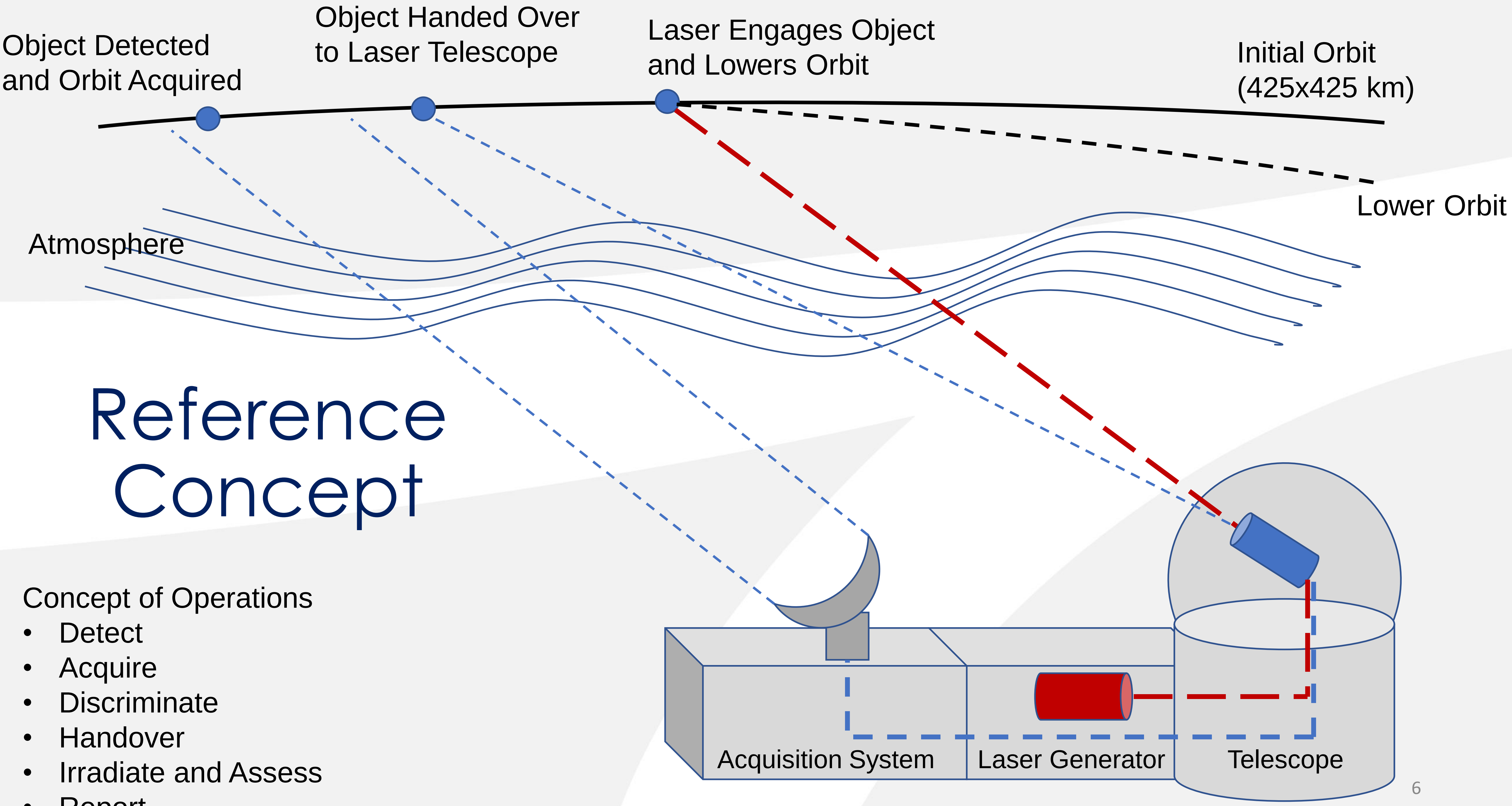
Reference Concept

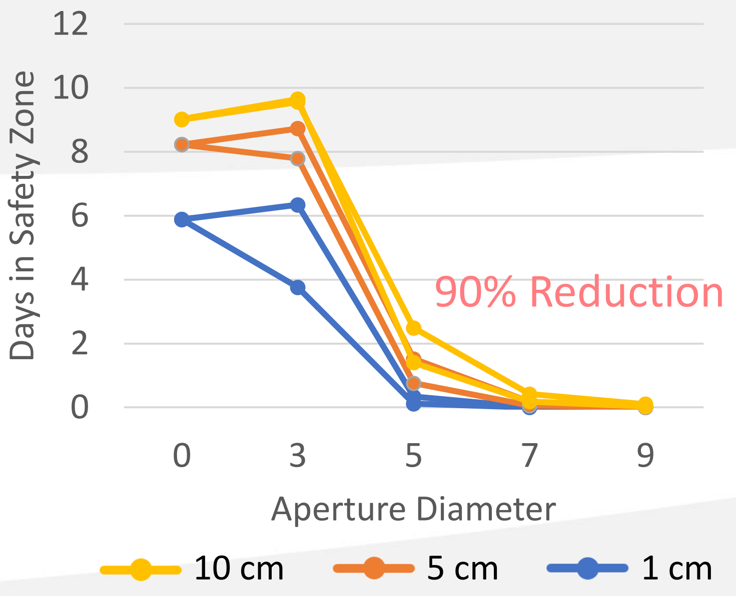


Concept of Operations

- Detect
- Acquire
- Discriminate
- Handover
- Irradiate and Assess
- Report

Selected Trades (16 kJ Laser)

Laser: 16 kJ, 10 ns, M^2=2



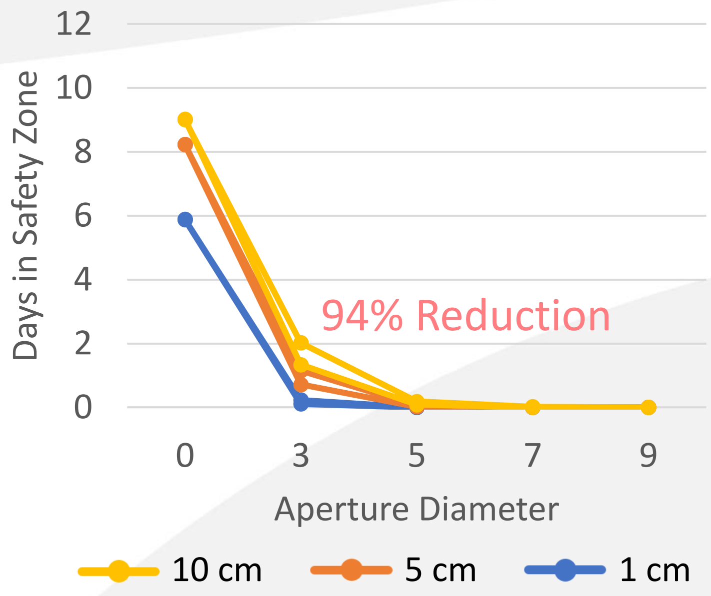
5-meter aperture is required to reduce risk by 90 %

Improve Beam Quality to near 1

Reduce Pulse Width to 1 ns

Do either of these and a 3-meter aperture is required to reduce risk by 70 %

Laser: 16 kJ, 1 ns, M^2=1



3-meter aperture can reduce risk by 94 %

Notes:

- Zero-meter aperture is the baseline case where the laser is not used.
- Variation in curves is due to geometry of overflying debris. Varies from debris flying directly overhead to +/- 5 degrees.
- All risk reductions are weighted by the number of debris at each 1 cm size interval

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Takeaway from Technical Interchange Meeting

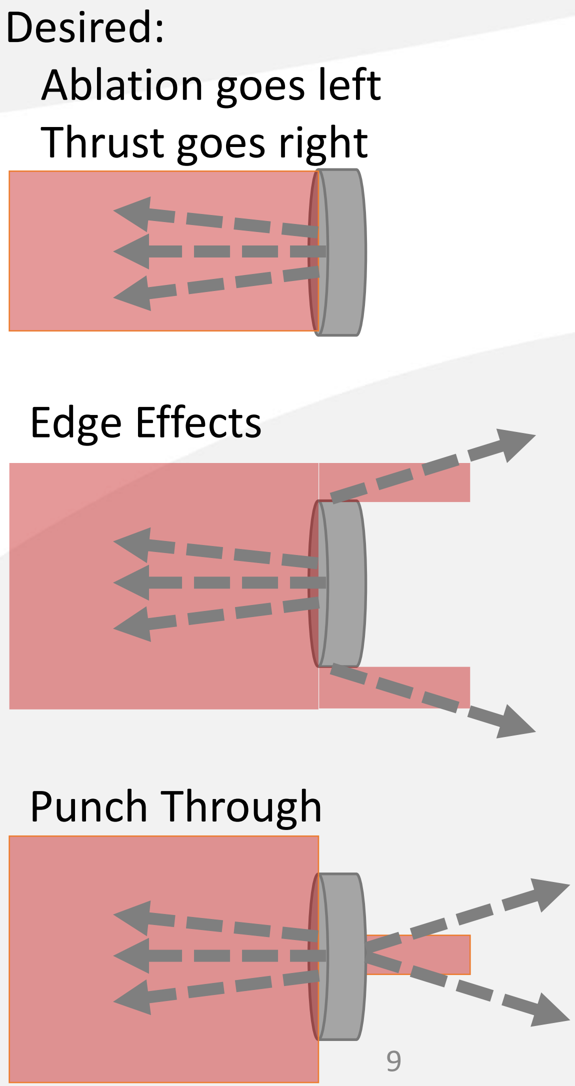
- Most experts thought it is technically feasible to perform the concept of using a ground-based laser to protect crewed platforms from centimeter-size debris
  - Some of the possible systems in the OTPS trades are nearly within the state of the art
  - Demonstration missions may be possible with existing laser and beam director technologies

- Others believed that the concept required adaptive optics capabilities that are far beyond the state of the art
  - These experts were unaware of relevant defense capabilities claimed by other participants
- Most believed that alternative ground- and space-based laser concepts might deliver greater performance or lower cost

Make or Break #1: Realistic Test Data

- There is very limited experimental data to characterize the interaction of representative laser beams with realistic debris

Issue	Existing Data	Realistic Scenario
Rep Rate	Single-shot	Rep-rated, may see up to 3x reduced coupling
Overfilled	The object is much larger than the laser spot	Laser spot is ~50 cm on a cm-sized debris
Variance of Fluence	Clean beam to the object	Beam significantly altered by the atmosphere
Shape	Test articles are clean, flat, smooth, and single-material	Debris is dirty, oddly shaped, rough, and multi-material
Breakup	Objects are thick enough to avoid spall or punch through	Debris may be small enough for punch through or fragmentation



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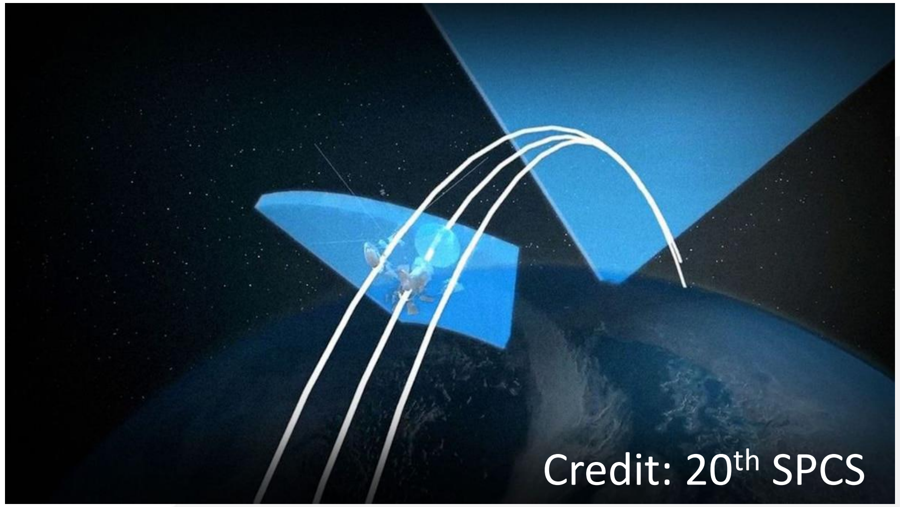
Make or Break #2: Find, Fix, Handover

- The ability to find, fix, and handover custody of centimeter-size debris to a laser beam director has not been demonstrated
  - Very little time to engage the debris; time taken gaining custody reduces time engaging debris
- State of the Art
  - Demonstrated un-cued detection with radar to tip and cue a large telescope for space objects larger than 10 cm
  - Laser ranging of <10 cm debris in LEO was demonstrated by EOS Space in 2014
- Can likely close this shortfall with existing S- or X-band radar, acquisition tracking sensors, and large beam director



Space Fence radar as seen from space

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Make or Break #3: System Modeling

- Lack an in-depth performance model for the system that can support architecture and conceptual design studies
- The requirements for each sub-system closely depend on each other, making it difficult to factor the problem into discrete steps and to make trades among them
- Suggested modeling approach:
  - Do not push state-of-the-art in survivability of optics, size of beam director, or size of secondary mirror
  - Model of best possible AO system, within state of the art, under range of conditions
  - Integrate AO model and results from previous shortfalls into a system-level performance model
  - System-level performance places requirements on the laser
  - Design study of laser, if necessary

Other Insights (Lasers)

- Lasers in the concept are beyond the state of the art (~1 um, ~10 kJ, ~10 ns, ~10 Hz);
  - No fundamental issues with scaling up to this level
  - Easier to build one large laser than to spectrally combine many smaller lasers
- Glass Lasers
  - Thermal management at this scale not demonstrated
  - Diodes are expensive
- Excimer
  - Can scale pulse energy up without issue
  - Would be difficult to extend rep rate beyond 5 Hz
  - Seems much cheaper option, but less heritage

National Ignition Facility

ELECTRA Laser

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Other Insights (Pre-Compensation)

- Point ahead problem can be solved with multiple laser guide stars
- Participants divided on ability to correct for tip/tilt
  - Some did not believe would get enough returned photons from the object
  - Fugate (2003) demonstrated use of reflected sunlight and natural guide stars to deliver a pre-compensated beam to a satellite at 800 km
- Need to characterize the Strehl ratio as a function of elevation angle that is possible for the reference concept

Telescope at Starfire Optical Range

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Other Insights (Misc)

- Non-Linear Effects to Beam Propagation
  - Can be avoided by siting the laser a few kilometers above sea level
  - May allow for very short pulses widths, which opens up trade space
- Survivability of Optics
  - Do not push the state of the art here
  - If the secondary mirror can survive, the primary will be fine
    - A 60 cm mirror with a 10 kJ pulse will have a fluence around 3.5 J/cm2, well within SOA for coatings
  - Acceleration of dust is not a reliably solved problem for directed energy weapons
    - Debris remediation system would operate in far more benign conditions

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Tell Us What We Missed

- Using a ground-based laser to protect crew on ISS from cm-size debris seems feasible
- Have identified the major technical issues that remain and looking for help to address or refine them

Backups

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Selected References (with comments)

- The pioneering study of debris remediation with a ground-based laser. Quite dated by now, but contains 350 pages of in-depth equations, calculations, data, and graphs. Note Strehl ratio is 0.5!
  - 1996. Campbell et al. Project ORION: Orbital Debris Removal Using Ground-Based Sensors and Lasers
- Update to Campbell. Strehl ratio of 0.25 (all from beam quality M^2=2) and 13 m aperture (!), but this is for reaching particles with apogees as high as 1000 km. Our use case is only 425 km altitude.
  - 2011. Phipps et al. Removing Orbital Debris With Lasers
- Strehl ratio as function of elevation angle, varies from 0.05 to 0.35.
  - 2021. Scharring et al. LARAMOTIONS: a conceptual study on laser networks for near-term collision avoidance for space debris in the low Earth orbit
- Fluence on debris as function of altitude and irradiance angle. Good discussion of inefficiencies with the laser-debris interactions.
  - 2021. Scharring et al. Ablative collision avoidance for space debris in the Low Earth Orbit by a single multi-kJ pulse from a ground-based laser
- Updates on the previous two studies, including thermal effects on lased debris, and seems to indicate that ground-based laser removal doesn't work! Did not consider thermal radiation of debris to cool it. Is melting bad?
  - 2023. Scharring and Kaestel. Can the Orbital Debris Disease Be Cured Using Lasers?
- Using machine learning to improve the Strehl ratio for tracking a fast-moving object.
  - 2021. Chen, Shah, and Liu. A U-Net-Based Neural Network for Predictive Adaptive Optics

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Concept of Operations 1/2

Lasers or other forms of directed energy can impart force on an object without making physical contact. This reference mission focuses on creating force-at-a-distance using ablation. Figure 1 provides a general illustration of a facility that could provide such a capability. **The goal of the reference mission is to protect crewed platforms in LEO from potentially lethal strikes of currently untracked orbital debris in the 1-10 cm size range.**

The laser removal system has four main hardware components: a laser generator, a telescope through which the laser beam is focused and fired, a laser guide star and adaptive optics system to correct for atmospheric distortions of the beam, and a method for getting an accurate orbital determination of the debris to guide the telescope. Debris in the 1-10 cm range is not trackable in the same sense as larger debris; the orbit of the large debris is determined with sufficient precision that the same object can be reacquired later. However, small debris may be sufficiently trackable for removal, by using a radar or passive optical capability to track the debris immediately after its detection. There may be no need to reacquire the debris on subsequent orbital passes—only to track it across the sky long enough for a laser to engage it.

With ablation, a laser beam strikes a surface with enough intensity to ablate material, which is ejected approximately perpendicular to the surface and generates thrust in the opposite direction. In general, the ejected material is a combination of hot gas and plasma and therefore does not contribute new debris to the environment. Applied to debris, ablation can generate far greater levels of thrust than photon pressure but requires more powerful laser beams and greater optical precision. Ground-based experimental data and simulations of laser ablation on space debris indicate that this mechanism can de-orbit both non-trackable and trackable debris.

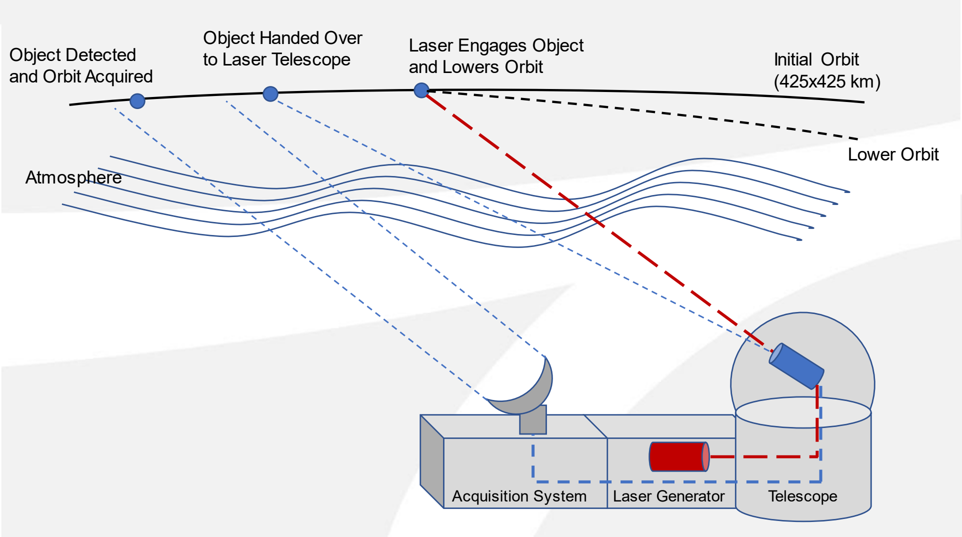


Figure 1. Notional concept of a ground-based laser facility for imparting impulses to orbital debris. The telescope that focuses the laser may require advanced adaptive optics to correct for atmospheric distortions to the beam.

Concept of Operations 2/2

The concept of operations (CONOPS) for remediating small debris with a ground-based laser proceeds as follows:

- **Detection**. A radar or passive optical method operates in stare-and-chase mode, waiting to detect a debris object at altitudes around 425 km. This allows the debris to be remediated before its orbit decays further and begins crossing the path of crewed platforms near 400 km.
- **Acquisition**. Once the object has been detected, the radar or optical method transitions from “stare” to “chase” mode. During this time, the precision of the object’s orbit is refined sufficiently to maintain custody of the object for only a few minutes. For small debris removal, the radar or optical method needs only to be able to track one object at a time and just long enough to engage it with a laser.
- **Discrimination**. The object is confirmed to be a piece of debris with physical and orbital properties that make it amenable to removal with the laser system. Further, the remediation system calculates the planned path that the laser beam will sweep across the sky and guarantees that no other space objects or aircraft will be illuminated by the beam.
- **Handover**. Tracking of the debris transitions from the radar or passive optical system to the laser system in preparation for the irradiation of the object. Handover is complete when the debris is reliably boresighted by the telescope.
- **Irradiation and Assessment**. The laser irradiates the debris to nudge it. After every laser pulse, a flash of plasma should be detectable, indicating successful ablation. Once the nudging is finished, the laser ramps down but continues to range the object until its new orbit is determined.
- **Book-keeping**. The results of the operation are recorded to ensure the risks to operational spacecraft are reduced and the throughput of the laser system is as expected.

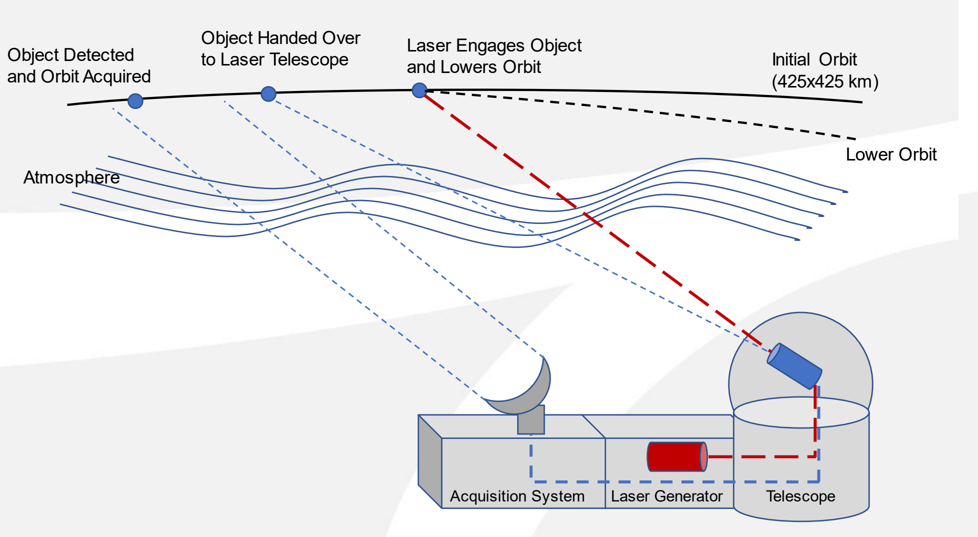


Figure 1. Notional concept of a ground-based laser facility for imparting impulses to orbital debris. The telescope that focuses the laser may require advanced adaptive optics to correct for atmospheric distortions to the beam.

Approach for TIM

Invited 19 attendees with expertise that cover these topics

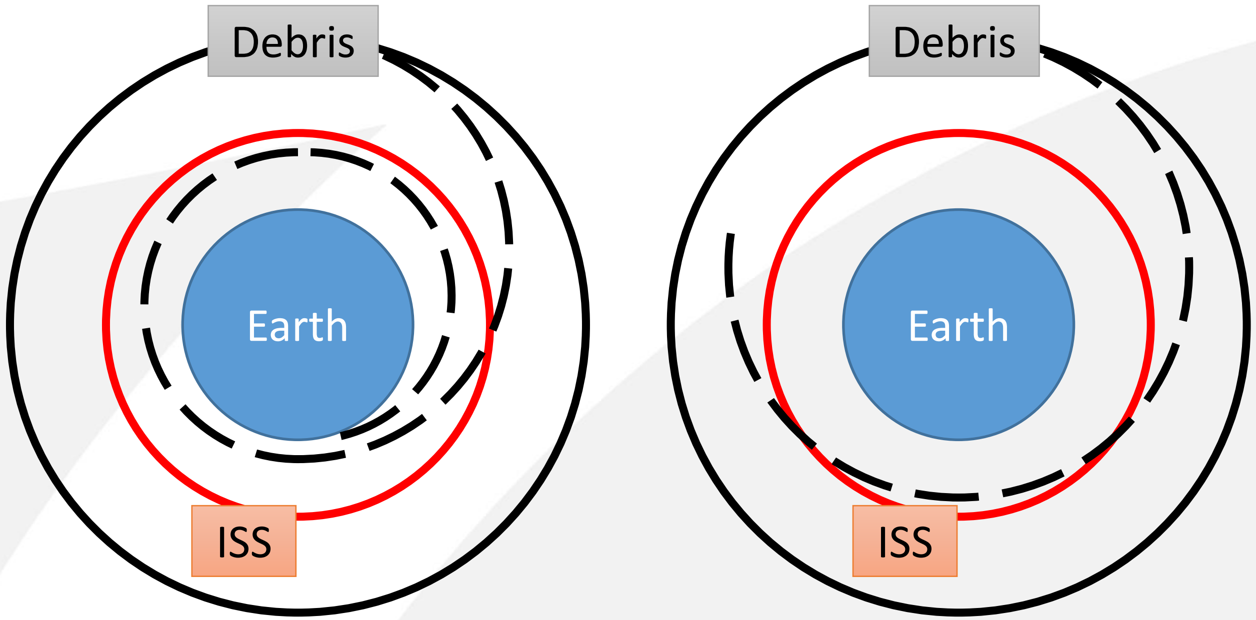
- Separate discussions around the major subsystems and physical phenomena:
  - Effect of the laser on debris
  - Detect debris and hand over to the beam director
  - Custody of the debris with large beam directors
  - High-energy lasers (glass and excimer)
  - Non-linear atmospheric effects to beam propagation
  - Beam pre-compensation
  - Survivability of the optics
- Within each discussion, participants were asked to consider and discuss the following questions:
  - What existing technologies or ongoing work might benefit the development of such a system?
  - What are the key challenges or gaps facing the technical performance of the system?
  - What technology maturation or tests could most effectively reduce the technical and cost risk of the system?

Effect of Nudging Debris

- Lowering perigee will:
  - Reduce time-to-deorbit
  - Make debris begin crossing ISS orbit sooner than otherwise
- Nudges must be strong enough to cause rapid reentry
- Weak nudges make things worse
  - Reduced deorbit time not enough to overcome earlier crossing time

Strong Nudge
Good

Weak Nudge
Bad



Assumed Parameters in Simulations

Debris
- Aluminum, rectangular prisms with aspect ratio 3
- Characteristic lengths of 1 - 10 cm
- Beginning orbit is 425x425 km with inclination of 40 degrees
- Drag coefficient 2.2

Detection and Handover
- Debris is detected at 10 degrees elevation
- Time from detection to acquisition by telescope: 20 seconds
- Followed until pulses would no long be pushing debris retrograde, about 3 minutes.

Laser
- Located in Texas, near Hobby Eberly Telescope (30.7N, 104.0W)
- Provides pulses that are 8-16 kJ, 1-10 ns, 16 Hz, at 1064 nm
- Beam quality M^2 = 1-2

Telescope
- Primary aperture 0-9 meters diameter
- Strehl ratio contributions from:
    - Anisoplanatism. From 0.25 to 0.1 as aperture increases; constant over elevation
    - Tilt. 1
    - Laser Beam Quality. $1/M^2$

Laser-Debris Coupling
- Fluence threshold of 3 J/cm^2 at 10 ns and 1 J/cm^2 at 1 ns
    - Debris ascends for another 40 seconds after acquisition before dV begins to be imparted
- No inefficiencies due to debris shape, roughness, multi-material, spin
- Calculate if debris melts
- Only including dV in the retro direction, throwing away the radial dV.

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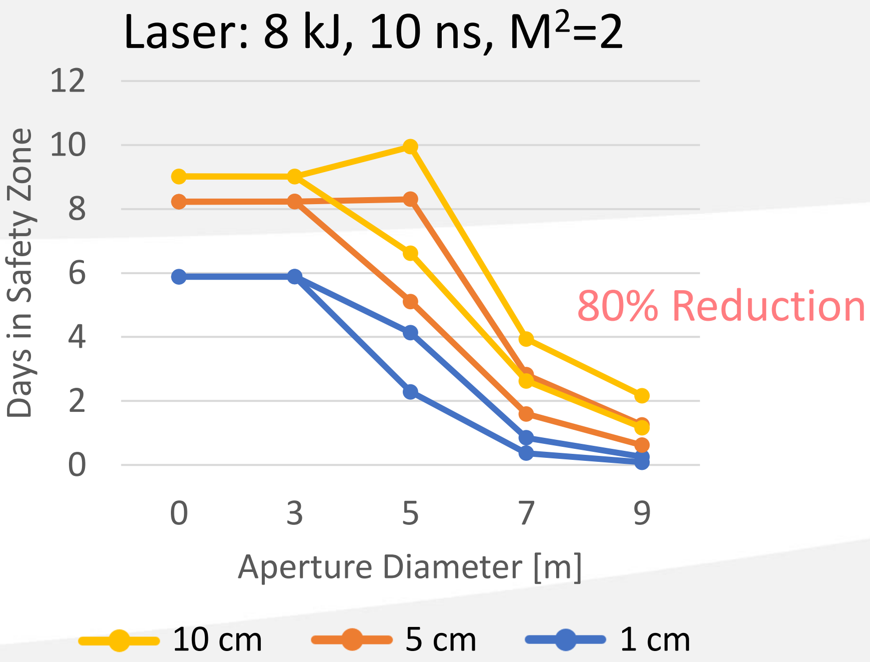
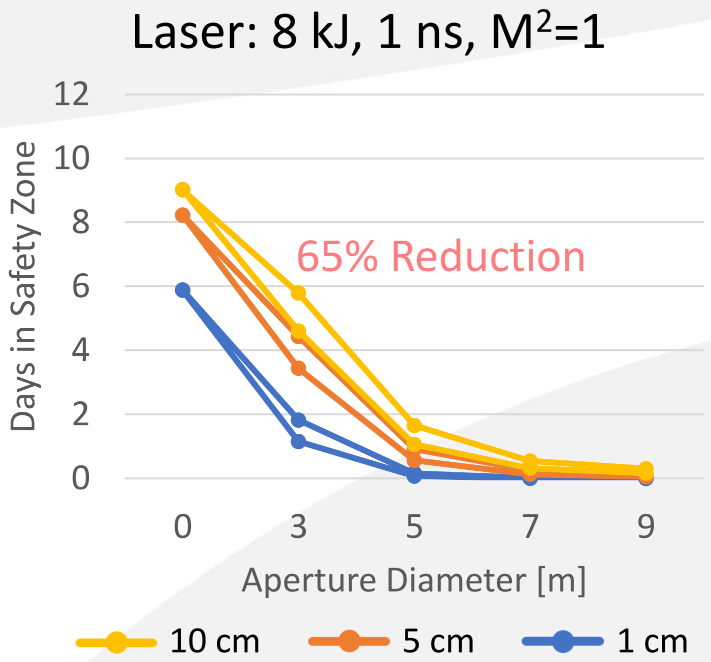
Selected Trades (8 kJ Laser)



Improve Beam Quality to near 1

Reduce Pulse Width to 1 ns



7-meter aperture is required to reduce risk by 80 %

Do either of these and a 5-meter aperture is required to reduce risk by 80 %

3-meter aperture can reduce risk by 65 %

Notes:
- Zero-meter aperture is the baseline case where the laser is not used.
- Variation in curves is due to geometry of overflying debris. Varies from debris flying directly overhead to +/- 5 degrees.
- All risk reductions are weighted by the number of debris at each 1 cm size interval

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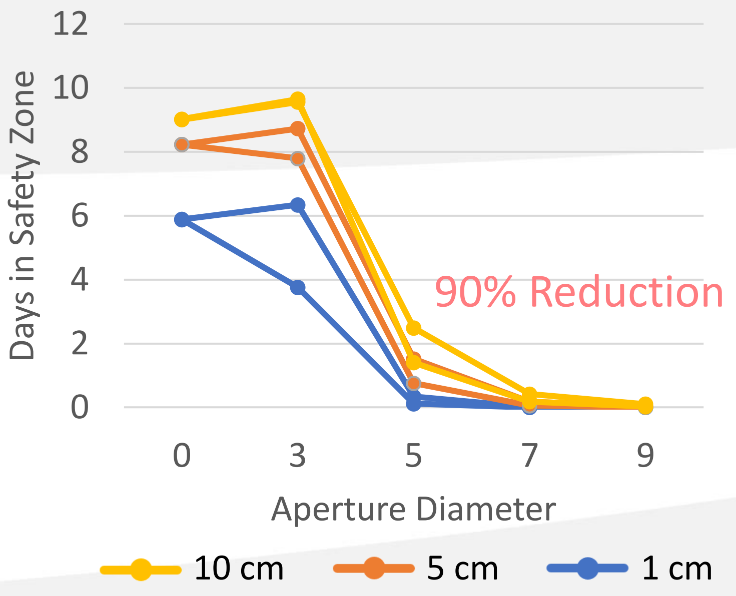
Selected Trades (16 kJ Laser)

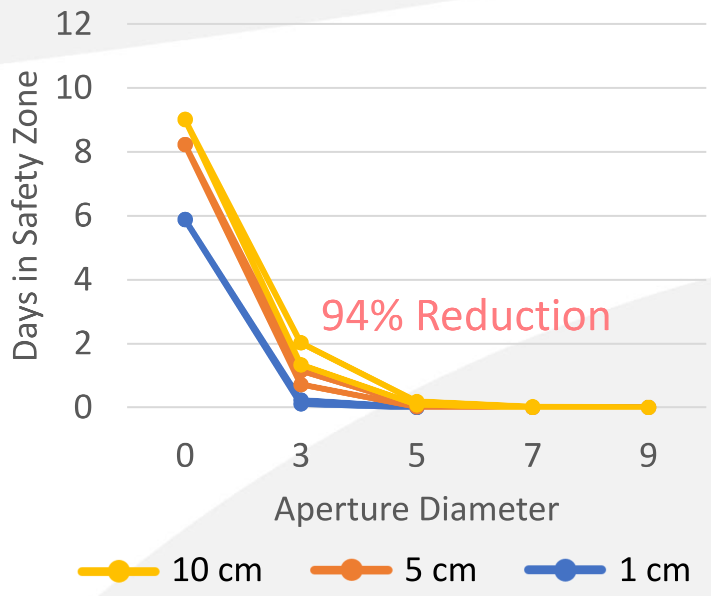
Laser: 16 kJ, 10 ns, M^2=2



Improve Beam Quality to near 1

Reduce Pulse Width to 1 ns

Laser: 16 kJ, 1 ns, M^2=1



5-meter aperture is required to reduce risk by 90 %

Do either of these and a 3-meter aperture is required to reduce risk by 70 %

3-meter aperture can reduce risk by 94 %

Notes:
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