SPACE DEBRIS REMOVAL USING A
HIGH-POWER GROUND-BASED LASER*

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Abstract

The feasibility of utilizing a ground-based laser without an
orbital mirror for space debris removal is examined. Technical
issues include atmospheric transmission losses, adaptive-optics
corrections of wavefront distortions, laser field of view
limitations, and laser-induced impulse generation. The physical
constraints require a laser with megawatt output, long run-time
capability, and wavelength with good atmospheric transmission
characteristics. It is found that a 5-MW reactor-pumped laser can
deorbit debris having masses of the order of one kilogram from
orbital altitudes to be used by Space Station Freedom. Debris
under one kilogram can be deorbited after one pass over the laser
site, while larger debris can be deorbited or transferred to
alternate orbits after multiple passes over the site.

Introduction - The Space Debris Problem

Hypervelocity collisions with artificial space debris are a
growing threat to the long-term safety of space assets in low-
earth orbit. Some encounters between assets and debris have
already occurred, and the frequency of such encounters is
projected to increase in the next decades. It has even been
argued that a debris "population explosion" could ultimately
occur as a result of debris-debris collisions.1-10

Space mission planners are concerned that Space Station Freedom
(SSF) could be crippled, if not virtually destroyed, by an impact
with debris. Due to its large cross-sectional area, its long
mission duration, and the eventual permanent presence of
personnel, SSF is perhaps the greatest potential victim of a
debris collision during the next decade or so. An impact by
debries having a 1-cm diameter could result in an energy release
comparable to that of a hand grenade.8 The frequency of such a
collision is estimated to be about once per decade, and that for
a collision with smaller debris would be even greater.11

Considerable effort has already gone into improving our
understanding of the threat posed by debris. NORAD has dedicated
a significant portion of its resources to detecting and tracking
debries, as well as to cataloging orbital parameters and albedos.
This information is made available to NASA so that collision
avoidance can be incorporated into the planning of every US space
mission.1,3

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The Defense Nuclear Agency (DNA) has funded the SOClT (Satellite Orbital Debris Characterization Impact Tests) program to study the generation of debris by collisions. A destructive test was conducted with an unlaunched satellite to determine the size and mass distributions resulting from satellite break-ups.12

Space debris studies have determined that there are about 3.5 million articles of debris now in orbit. About 25 thousand of these have diameters of 1 cm or more, and about 7 thousand have diameters of 10 cm or more. The distribution of debris by mass has also been determined. Debris with diameters of 10 cm or more make up all but 0.03 percent of the total mass in orbit. The remainder is almost entirely composed of debris with diameters in the range of 1 to 10 cm.1,3,13

The distribution of debris by altitude and eccentricity has likewise been determined. Most debris is found in roughly circular orbits, with the population achieving a maximum at orbital altitudes near 800 km.1-3 However, enough debris exists at lower altitudes to present a real threat to SSF. The material makeup of debris has been found to be the same as that of the rockets and spacecraft that produce it. Common materials include aluminum, steel, glass, circuit boards, plastics, and surface coating materials.1,6,13

Debris Mitigation Methods

Measures for reducing the threat posed by artificial space debris generally fall into the four categories of prevention, shielding, avoidance, and removal. Prevention consists of adopting standards for design, construction, launch, and deployment. The goal is to diminish the amount of debris deliberately put into orbit during normal space missions.

Shielding spacecraft against micrometeor impacts has been in use for decades. Today the threat posed by artificial debris exceeds that due to meteors, at least for low and intermediate orbital altitudes.1,10 Consequently a number of new designs for passive debris shields have been proposed.5,13,14 These offer protection against the more probable encounters with debris having diameters up to about 1 cm. Unfortunately they add significantly to the launch weights of the protected assets. Passive shields will never be able to provide protection against debris with diameters much greater than 1 cm because of the unacceptable weight penalty required.3

Detection and avoidance has been used for years, particularly for manned missions, with tracking and maneuver command generation being done from the ground.1 Recently there has been interest in providing assets with onboard automatic detection and maneuvering. An infrared or radar detector would identify potential threats, while an automatic control system would command the maneuvers. Unfortunately, these capabilities imply
penalties with regard to launch weight, space power, system complexity, and mission duration.6,15

Mechanical debris sweepers have been proposed for active removal of debris. One design consists of panels extending outward from a central body. The sweeper would necessarily be very large and would require considerable time and expense for in-orbit assembly and maintenance. It would also be relatively complex if autonomous surveillance and maneuver capabilities are included. An encounter with a large piece of debris or a functioning asset could cause the total breakup of the sweeper and the addition of more debris to the already growing population. Other proposed sweepers have similar problems.7

It has also been proposed that space-based lasers and particle beam systems could be used to actively remove space debris. These would be capable of delivering highly concentrated power to small areas at long ranges. The power delivered would be utilized to totally vaporize the debris or to impart delta-velocity for the perturbation of orbital parameters.16-18 Basing directed-energy systems in space would have all of the disadvantages associated with large space platforms requiring high power and maneuverability. The costs involved in launching and maintaining such systems would be prohibitive.

An alternative approach, at least for the case of lasers, is to base the directed-energy system on the earth's surface. This would greatly reduce the problems associated with technology requirements, launch and assembly costs, space power, thermal dumping, and maintenance. Laser power at an appropriate wavelength could be beamed directly from the ground to orbiting debris or it could be redirected to the debris with the use of an orbital mirror.

This report focuses on debris removal using a ground-based laser without an orbital mirror. The costs of launching and maintaining a mirror of the size required would be prohibitive. It will be shown that the proposed system can remove debris with masses of the order of one kilogram from SSF altitudes. The specific laser performance parameters used in the supporting analysis are based upon observed and projected capabilities of the FALCON (Fission Activated Laser CONcept) reactor-pumped laser currently under development at SNL, in cooperation with Idaho National Engineering Laboratory and others.19-22

### Nominal Design Parameters

The proposed debris-removal system consists of a ground-based reactor-pumped laser and a large steerable beam director with adaptive optics capabilities. The system is designed to beam laser power to orbital altitudes where it will ablate debris surface material, generate impulse, and produce predictable orbital perturbations. Nominal design parameters are specified for each subsystem, beginning with the laser.
The FALCON reactor-pumped laser at Sandia operates in continuous-wave mode with relatively high efficiencies at wavelengths of 1270, 1733, 1790, and 2030 nm. The first two are attractive from the standpoint of atmospheric transmission. In this report it will be assumed that the 1733-nm line is being used. The continuous-wave power output of the laser is assigned the nominal value of 5 MW, which is sufficient to produce debris surface ablation after atmospheric losses. Average powers of this magnitude can be achieved with a reactor-pumped laser like FALCON, because its power output is intrinsically scalable. Reactor-pumped lasers are also capable of long run times, which is a requirement for removal of orbital debris.

The laser beam is optically processed by a beam director having a 10-meter-diameter mirror and adaptive optics capabilities. Beam correcting mirrors of this size are feasible, as is demonstrated by the installation of the Keck telescope mirror. The beam director is assumed to result in no loss of radiant power. Adaptive optics is very effective in the near-infrared where the distortions due to atmospheric turbulence are minimal. A distorted beam can be restored to a diffraction-limited intensity distribution, except for an overall spreading of the beam. The Strehl ratio is the measure of this spreading and is assigned the nominal value of 50 percent in this report. Adaptive optics can correct for wavefront distortions for angles off zenith (vertical) up to about 60 degrees. The laser beam angle will not exceed this value in the analysis reported here.

The debris to be removed is assumed to be a section of aluminum sheet with a thickness of 0.5 cm and an area of 1000 cm$^2$. The debris orbit is assumed to be circular with an altitude of 350 to 450 km (SSF altitudes) and to pass directly over the laser site. The effects of debris rotation are accounted for by time-averaging the direction of the impulse imparted by laser ablation. The impulse parallel to the laser beam will be one-half maximum and that perpendicular to the beam will be zero.

The impulse and delta-velocity are imparted directly to the debris by way of laser-induced surface ablation and impulse generation. The laser power delivered to orbit is reduced by atmospheric absorption and scattering. In this report the transmission coefficient is assumed to be 80 percent for vertical propagation. The laser intensity distribution is distorted by atmospheric turbulence, but is corrected by adaptive optics. The result is an intensity distribution that is approximately Gaussian. Its width is given by the Gaussian radius where the intensity is about 36.8 percent of its maximum value.

The reflectance of laser radiation by the debris surface depends upon the nature of the surface and the intensity of the radiation received. The condition of the surface is expected to be much poorer than that of a newly produced piece of aluminum. In
addition, metal surfaces undergo abrupt decreases in reflectivity when irradiated with high-intensity laser beams. This change is associated with melting and vaporization and can result in reflectivity values in the vicinity of 50 percent. This value was assumed in the generation of this report.

For most materials, surface melting and vaporization will occur with an absorbed intensity of 10 kW/cm² or higher, assuming sufficient irradiation time. From the absorbed fluence (energy/area) at the surface, the impulse per unit area can be estimated using empirical results. Laboratory measurements with aluminum "targets" at wavelengths around 1000 nm show that the ratio of impulse/area to absorbed fluence is 1 dyne/watt or greater. This value was assumed in the generation of this report. It is regarded as conservative and is consistent with first-principles models of laser ablation.

The firing strategy used allows debris to be irradiated for the longest possible time. The laser is first fired as the debris approaches the site from the west at an angle off zenith of no greater than 60 degrees. The laser continues to fire until the debris passes directly over the laser site. The total time available is 75 to 95 seconds for debris at SSF altitudes.

A consequence of this firing strategy is that the imparted delta-velocity will have a component opposite to the debris velocity vector and another parallel to the orbital radius vector. The effect of the delta-velocity on the orbital parameters can be determined using orbital perturbation theory. Both the semi-major axis and orbital eccentricity are affected. The orbit becomes elliptical with the perigee located on the side of the earth opposite to the laser site.

Results and Conclusions

Computer modeling was performed to simulate the processes involved in laser debris removal. A FALCON ground-based laser was assumed to emit radiation at 5 MW and 1733 nm. The beam director mirror diameter was chosen to be 10 meters and the Strehl ratio of the corrected beam was set at 50 percent. Aluminum sheet material was selected as the debris, and was assumed to be in a circular orbit with its altitude ranging from 300 to 475 km.

Modeling results are summarized in the figure included. As expected, debris removal capability is greatest at lower altitudes. Note that a 0.9-kg article of debris can be deorbited from 300 km altitude after a single pass over the laser site, and that the mass increases to just over 4 kg when five passes are allowed. In contrast, for orbital altitudes of 475 km, the mass is just over 0.01 kg for one pass and about 0.08 kg for 5 passes.

SSF altitudes range from about 350 to 450 km and are indicated in the figure. In one pass over the site, the mass removable is almost 0.5 kg at the lower altitude extreme and about 0.06 kg at
Maximum Debris Mass Removable

5 passes over site

Initial Orbital Altitude (km)

Maximum Debris Mass (Kg)
the upper extreme. The mass removable increases with the number of orbital passes allowed. For five passes it increases to about 2.5 kg for 350 km and to almost 0.03 kg for 450 km.

Other important conclusions were obtained from the modeling that are not shown in the figure. For example, it was determined that laser ablation of debris at SSF altitudes becomes feasible when laser output (at 1733 nm) is somewhat over 2 MW. This power level represents an approximate lower limit for a ground-based laser to be used for space debris removal.

It was also found that the ability of a ground-based laser to deorbit debris from 800 km altitude requires a power output approaching 15-MW. Such a system could deorbit 1-kg debris after one pass over the site. It could deorbit or perform orbit transfers for larger debris after multiple passes over the site.

In conclusion, utilizing a ground-based laser to remove debris from low-earth orbit is feasible and economically attractive. It does not involve launching any systems into orbit. This increases cost effectiveness and avoids the creation of additional launch-related debris. It requires a laser source and beam director located on the ground. This means that near-term technologies will suffice for the construction and operation of the system.

Remaining Issues

Several issues relating to laser debris removal have not been addressed. One important question is whether sufficient impulse can be generated without causing debris breakup. Naturally this depends upon the material makeup and general condition of the debris itself. Judging from the magnitudes of the pressures and forces observed in computer simulations, it is reasonable to conclude that breakup is not likely in most cases.

A related concern is the production of debris by the material ablated from debris surfaces. Laboratory tests indicate that such particles will have sizes of the order of a micron or so. Relatively large numbers of these could be produced, but their sizes are such that passive debris shields could protect space assets from the effects of their impacts.28-30

An additional issue is related to the requirement that the laser beam be held on the debris continuously for tens of seconds. The beam director mirror has to be rapidly steered with high accuracy, or else the laser-induced impulse will be intermittent, at best. For the SSF example, the mirror would have to be steered at roughly 1 milliradian/second with a pointing accuracy of just under 1 microradian. This is within the capabilities of near-term tracking and pointing systems.
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