ORION: Clearing near-Earth space debris in two years using a 30-kW repetitively-pulsed laser

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ABSTRACT

Nearly 200,000 pieces of debris in the 1 – 20-cm range in low-Earth orbit (LEO), a legacy of 35 years of spaceflight now threaten long-term space missions. An economical solution to the problem is to use a ground-based laser to create a photoablation jet on the objects and cause them to re-enter the atmosphere and burn up. A sensitive optical detector is required to locate objects as small as 1 cm at 1500 km range. Applied when the object is rising and between about 45 and 15-degree zenith angle, the necessary Δv is of order 100m/s. A laser of 30 kW average power at 5-ns pulsewidth and a 4–6-m mirror with adaptive optics can clear near-Earth space of the 1–20-cm debris in 2 years of operation. A high altitude site minimizes turbulence correction, interference from nonlinear optical effects, and absorption. We discuss the effect of nonlinear optical processes in the atmosphere as boundaries on propagation, and how to choose system parameters to guarantee optimum conversion of laser energy to target momentum. The laser might be Nd:glass (1.06µm/530nm), or iodine (1.3µm).

1. DEBRIS

Thirty-five years of space activity have produced several hundred thousand pieces of space debris larger than 1 cm in near-Earth orbit [Phipps, *et al.* 1996] (Fig. 1). Debris objects are now sufficiently numerous to pose a significant threat to the International Space Station Alpha (ISSA). For ISSA, the impact velocity spectrum of these objects peaks at 10–12 km/s, for which a 1-cm-diameter aluminum object has kinetic energy ≈ 100 kJ. The size range of greatest hazard to spacecraft is 1.5–20-cm. It is possible to shield against objects smaller than 1.5 cm. Larger objects are few, and can be seen and avoided. Cumulative debris flux in the 800-1100-km altitude band in this size range (meaning impacts from objects with size ≥d) is about 9E-5/m^2 cross-section per year [Kessler 1995a]. Today, space debris in low-Earth orbit (LEO) threatens any mission in the h = 1000 km vicinity which has a product of exposed area and on-station lifetime of the order of 10^4 m^2 – years. For example, a fleet such as that planned by Teledesic Corp. with orbit-average projected cross-section of 8.3E4 m^2 is expected to experience a hit once every 2 months. These hits are not necessarily catastrophic, but 3-4 satellites in this constellation will be lost to debris at a cost of $30-$40M in a decade [Stewart 1996].

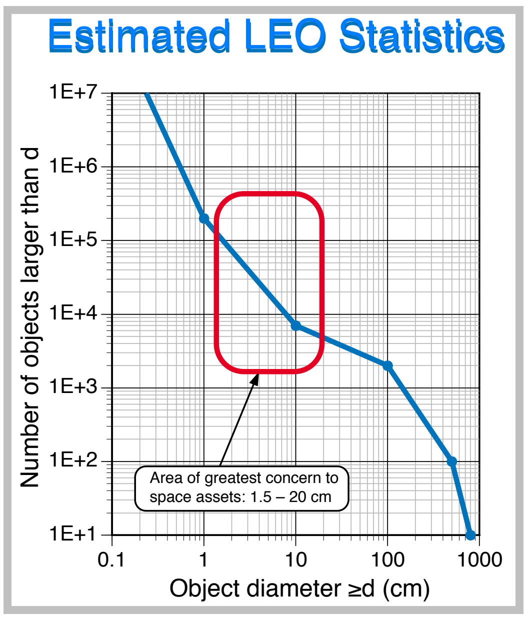

Figure 1
Estimated number of debris vs. size

There is still substantial uncertainty amounting to factors of 3 or 4 in the 1–20-cm flux because only the 7900 objects larger than 10 cm have been catalogued. Density of smaller objects is based on sampling [see, e.g., Stansbery, 1996]. A pernicious aspect of the debris arises from the possibility that collisions between these objects will produce many smaller objects. Some authors suggest the critical debris density for this effect has been achieved in this band [Kessler 1995b]. This process is irreversible in the popular 800–1100-km altitude band where lifetime is of order 10k yr.

2. WHY DEBRIS MITIGATION IS IMPORTANT

2.1 Protecting the Space Environment

Space is a commons. This last and most pristine frontier is being polluted.

2.2 Insurance policy

Presently, the users of space have mostly decided to assess the threat of space debris in terms of their individual assets. On the basis of the threat to an individual satellite, one can ignore the risk. Instead, we believe it is logical to look at the collective risk, since the total threat to World installed space assets (of order $60B) is significant, but may be mitigated, as in the case of the threat of collision to a fleet of automobiles, by pooling the risk in an insurance policy. That insurance policy is ORION, and its construction can be completed for a premium of about 0.2% of the installed capital investment.

2.3 Technology base

This project is the first opportunity to build a high average power, high peak power laser system. Its technical requirements also stretch existing capabilities in pointing, tracking, acquisition, detection, and adaptive optics.

2.4 Debris database

Small objects in the threatening 1-20-cm size range have mostly not been characterized, leading to unacceptable uncertainties in number density, flux, and orbital parameters of the objects.

3. PREVIOUS MITIGATION EFFORTS

Mitigation of debris has been discussed by Metzger, *et al.* 1989, Loftus & Reynolds 1993, Monroe 1994, Phipps 1993, and Phipps *et al.* 1996. A major policy document in this area is the Interagency Report on Orbital Debris [OSTP 1995].

The approach of Metzger, *et al.* is space-based, featuring a nuclear-powered spaceborne debris sweeper powering a neutral particle beam or a 10-kJ, 1-Hz krypton fluoride laser (λ = 248 nm). The advantage of this concept is that the photoablation thrust vector averaged over many laser shots can be directed exactly opposite to the momentum of the object for maximum efficiency, which cannot be done from the ground. The disadvantages are that mass costs \$10 – 20/g to put in low Earth orbit, plus the fact that the complexity of a space-based debris sweeper far exceeds that of the Hubble Telescope, which was a multi-billion-dollar effort both to install and to service. Also, because of the 1000-km depth of the debris band, space-based debris sweeper needs a range of action which turns out to be not dramatically different from that of its ground-based counterpart to be effective in a reasonable time. Finally, a space-based system discards a "free" advantage of the ground-based system since, from the ground, interesting objects are all moving against a fixed background, whereas, in space, velocity discrimination must be used, leading to complicated detection schemes involving 4-wave mixing. Monroe 1994 proposes a ground-based system featuring a 10-m-diameter beam director with adaptive optics correction and a 5MW reactor-pumped 1.73-µm wavelength laser. Loftus and Reynolds 1993 catalog forces available for removing objects from orbit, including direct propulsion, enhanced aerodynamic drag, solar sails, electromagnetic drag, and solar/lunar orbit perturbations. They also mention valuable efforts at international cooperation and improved spacecraft design to dramatically reduce the rate of increase of debris.

4. THE ORION SYSTEM

4.1 Overview

A ground-based, repetitively pulsed laser system with about 30kW average power (Nd:glass at 1.06µm is assumed but frequency-doubled Nd:glass, or iodine at 1.3µm have not been ruled out) is focused on the debris object by a 6-m diameter beam director fitted with adaptive optics capable of correcting atmospheric turbulence well enough to achieve a Strehl ratio of 0.5. Pulse energy is 30kJ. The system is installed at a high altitude, low-latitude site with good seeing to minimize the difficulty of attaining this goal. The laser pulse intensity on the debris object is adjusted so that a photoablation jet is created. Since most irregularly-shaped debris objects were created by explosion or collision, they will be tumbling about 3 axes, and this tumbling combined with operation near the photoablation threshold intensity will produce a net thrust averaged over many laser shots which is approximately parallel to the laser propagation vector. If the system only addresses objects which are rising with zenith angle $45° < \theta_z < 0$ the object's perigee will be lowered sufficiently (200 km) to produce rapid re-entry and burnup. For many of the objects, this can be done in one pass. In order to send the ORION laser beam through the atmosphere, beam intensity must be low enough to avoid driving nonlinear processes at the pulsewidth employed. Those of primary concern are Stimulated Raman scattering (SRS), Stimulated Thermal Rayleigh Scattering (STRS) and nonlinear index (n_2). The system can clear near-Earth space of the primary threat debris population in about two years.

4.2 Pulsed laser format is preferable to CW

Our studies have shown that a CW laser (1.3–3.8 µm) would require a power of 5–10 MW to achieve good momentum coupling to a debris target at 1500 km range. We will show that only 30kW average power from a repetitively-pulsed ≈1µm laser is sufficient to clear near-Earth space debris in less than 2 years.

4.3 Momentum coupling coefficients are well known

By convention, the momentum coupling coefficient C_m is defined as the ratio of target momentum produced by photoablation to incident laser pulse energy:

$$C_m = \frac{m\Delta v}{W} \quad \text{dyne-s/J.} \qquad [1]$$

As incident pulsed laser fluence increases past threshold, C_m for a wide variety materials rises rapidly to a peak value in the range 2–8 dyne-s/J, declining slowly for higher fluence as ejecta velocity increases. We surveyed the results of 46 experiments in which the fluence Φ_{opt} for optimum coupling was measured, and determined that for a wide variety of possible debris surfaces, wavelengths ranging from 0.25 to 10.6 µm, and pulsewidths 100ps<τ<1ms, Φ_{opt} can be best fit by:

$$\Phi_{opt} = C\,\tau^{\alpha} \qquad \text{J/cm}^2 \qquad [2]$$

with α = 0.45 and C = 2.3E4. Thermal transient theory would, of course, give α = 0.5.

4.4 Pulsed laser energy and pulsewidth are determined

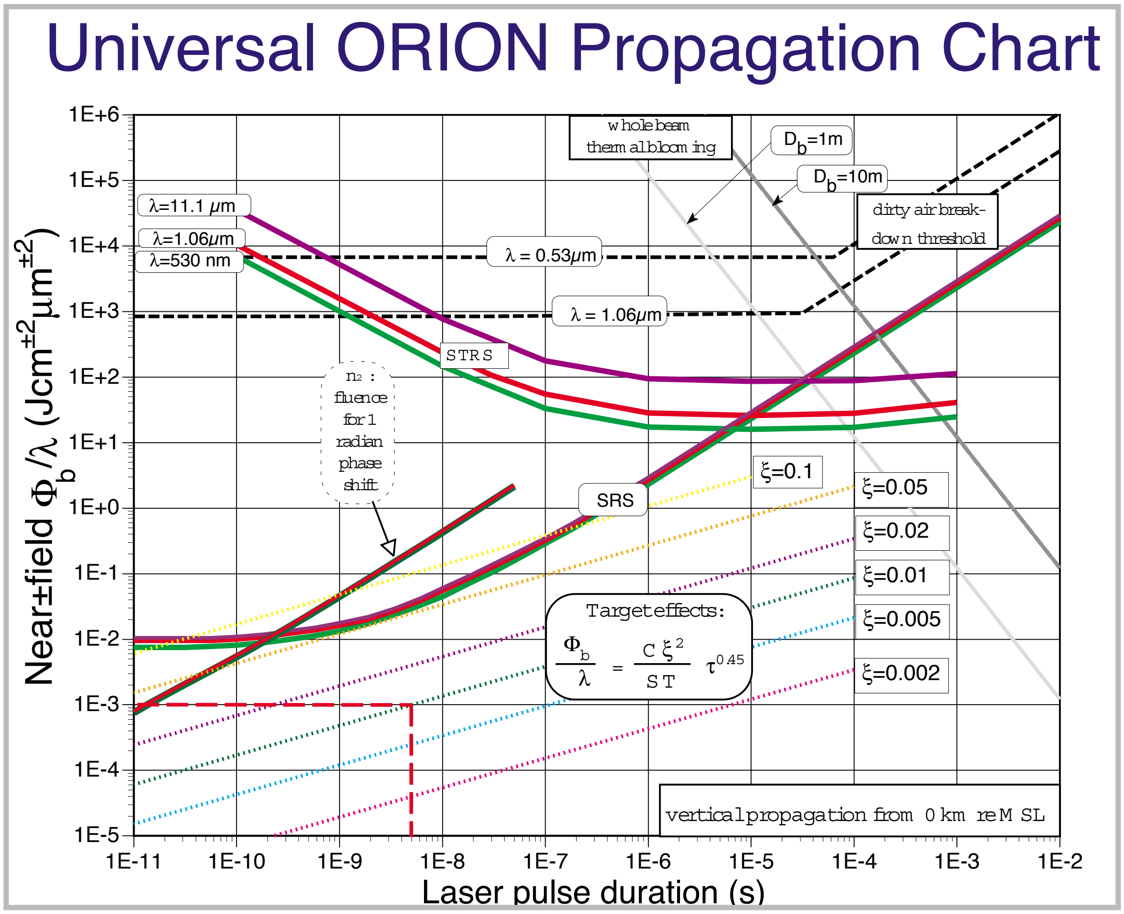

Figure 2. Graphical Solution to Target Physics and Nonlinear Atmospheric Transmission Limits

SRS and n_2 in the atmosphere are the limiting factors for beam pulse intensity. On the other hand, achieving optimum thrust at the distant target requires that a minimum fluence be delivered at range. Cost and agility set limits to the mirror diameter which can be used, and, hence, to beam diameter in the atmosphere. Given a wavelength, these effects together determine combinations of pulse energy and duration which satisfy both limits. That solutions exist is shown by Fig. 2. With laser pulse energy and beam diameter W_b and D_b, range z, wavelength λ, Strehl ratio S and atmospheric transmission T, fluence (J/cm^2) in each pulse Φ delivered to the debris is given by:

$$\Phi = \frac{\pi W_b T S}{4}\left(\frac{D_b}{z\lambda}\right)^2 \qquad \text{J/cm}^2 \qquad [3]$$

Equating [2] and [3] gives
$$\frac{\Phi_b}{\lambda} = \frac{C\,\xi^2}{S\,T}\,\tau^{\alpha}$$
for the necessary beam fluence at the ground. [4]

In Eq. [4], $\xi = z\sqrt{\lambda}/(\pi D_b^2/4)$. In the Figure, we have plotted lines of constant ξ (with D_b in m, λ in µm and z in Mm for convenience). It is seen that ξ = 0.05 pushes the nonlinear limits as hard as one dares in the 100ps–100ns range. This choice then fixes maximum system slant range z, once λ and D_b are picked. Note that the target effects lines move downward in proportion to the 4th power of D_b.

4.4 Number of targets, Δv for de-orbit and time for clearing debris determine laser average power

The present debris database cannot tell us the detailed composition of the 1–20-cm debris cloud. However, we have constructed a hypothetical [except for column A], representative 5-component cloud [Table I], and conclude from it that 30kW average power is sufficient to clear the population below 1500km in 2 yr. Average power is, of course, inversely related to clearing time. A 4–6-m diameter mirror is assumed. The laser might be a derivative of the DoE/Livermore National Lab de-

TABLE I: 30kW Average Power is Sufficient to Clear Hypothetical Debris Population in 2 Years

Target	A	B	C	D	E
Hypothetical Debris Item:⇒ **System Parameter:**	Na/K sphere	Carbon phenolic fragment	MLI (plastic/Al surfaces)	Crumpled Al	Steel tank rib support
Inclination (deg)	65	87	99	30	82
Apogee (km)	930	1190	1020	800	1500
Perigee (km)	870	610	725	520	820
A/m (cm^2/gm)	1.75	0.7	25	0.37	0.15
Actual size (cm)	1.0	1x5	0.05x30	1x5	1x10
Bond albedo	0.4	0.02	0.05/0.7	0.05/0.7	0.5
Optimum C_m(dyne-s/J)	6±2	7.5±2	5.5±2	4±1.5	4±1.5
Δv required (m/s)	190	110	140	90	160
Est. number of targets	50k	20k	60k	10k	10k
Laser re-entry effort:					
Shine time/item [30kW](min)	5	6	0.3	13	9
Retargeting time (min)	0.5	0.5	0.5	0.5	0.5
Total time all targets (yr)	0.5	0.3	0.1	0.3	0.2
Down time all targets (yr)	0.2	0.1	0.05	0.1	0.1
Total (yr)	0.7	0.4	0.15	0.4	0.3
[Grand Total (yr)]					**[1.95]**

sign for 1 of 64 arms of the National Ignition Facility (NIF) laser.

4.5 Acquiring/tracking debris

Probably the most difficult aspect in ORION is acquiring and tracking objects as small as 1cm at ranges up to 1500km. To clear 150k objects in 2 years, it is only necessary to acquire 17 objects /hr. Ho *et al.* [1993] have designed and tested a unique imaging, photon-counting detector which can see 1.3-cm objects with a geometric albedo of 8% at 400km range (or 100% at 1400 km) in solar illumination during dawn and dusk within a 1° field of view. Their detection algorithm is based on identifying linear tracks of single photons in x-y-t space containing, e.g., 16 photons during a 1-s interval. Even if 150k debris objects were uniformly distributed, acquisition rate within a 1° field of view would be 2.9/s. At this rate, a single detector operating only during the 3 hours of twilight can acquire the entire population in about 5 days. Using a slightly smaller field of view, background can be reduced sufficiently to acquire all targets of interest to ORION with a more-than-adequate data rate. As has been suggested [Phipps *et al.* 1996], a small, short-pulse tracking laser can develop an ephemeris for each object in 3 dimensions sufficiently accurate for the ORION laser to later find and act on the object in the dark (after a few orbits). This final process involves expanding the ORION beam footprint to match the few-m track uncertainty, using its beam as target illuminator, then progressively narrowing the footprint with the aid of a quadrant detector, computed relativistic lead angle, sodium beacon and adaptive optics. A polychromatic guidestar [Foy, *et al.*] may be of assistance.

5. PROBABLE SYSTEM COST

The 1500-km range all-optical system should cost of order $100–200 M, baed on costs of systems already built, as well as operating costs for manpower and consumables over a 2 – 3-yr operating life.

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